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Summary

A six-degree-of-freedom, ground-based simulator study has been conducted to evaluate the low-speed flight characteristics of four dissimilar cargo transport airplanes and to compare these characteristics with those of a large, present-day (reference) transport configuration similar to the Lockheed C-5A airplane. The four very large transport concepts evaluated consisted of single-fuselage, twin-fuselage, triple-fuselage, and span-loader configurations. The primary piloting task was the approach and landing operation.

The results of this study indicated that all four concepts evaluated had unsatisfactory longitudinal and lateral-directional low-speed flight characteristics and that considerable stability and control augmentation would be required to improve these characteristics (handling qualities) to a satisfactory level.

The primary pilot objections to the unaugmented handling qualities were (1) sluggish initial pitch response, (2) nonprecise attitude control due to large changes in pitch attitude caused by thrust variations and/or trailing-edge flap deflections, (3) sluggish roll response, and (4) difficulty in coordinating turns due to large sideslip excursions caused by control-wheel inputs.

Through the use of rate-command/attitude-hold augmentation in the pitch and roll axes, and the use of several turn-coordination features, the handling qualities of all four large transports simulated were improved appreciably.

The roll-performance parameter $t_{\phi=30}$ (time required to bank 30°) was examined quite thoroughly; and roll-response characteristics were predicted to be "acceptable" when $t_{\phi=30}$ was less than 6 sec and "satisfactory" when $t_{\phi=30}$ was less than 3.8 sec. In addition, it was determined that the maximum bank angle attained in the first second per unit of effective wheel deflection ($\phi_{1,\max}/\delta_{w,\mathrm{eff}}$) on the simulated very large transports can be correlated for pilot rating with previously published data (wherein much smaller transports were simulated). For a pilot rating of 3 (satisfactory), the value of ($\phi_{1,\max}/\delta_{w,\mathrm{eff}}$) was determined to be 0.1.

No problems were experienced because of engine failure for any of the simulated airplane concepts.

The handling qualities of the augmented very large transport configurations simulated (with the exception of the lateral-directional characteristics of the span-loader concept) compared favorably with the simulated reference transport.

Introduction

Transport airplanes have grown larger as technology has been developed, and even larger transports have been proposed to attain greater economy and performance. Several industry studies have indicated that aircraft capable of transporting large payloads for long distances appear feasible. Some of these concepts have estimated gross weights approaching 3 million pounds.

As previously stated in reference 1, for several years the aircraft industry has been aware that many of the existing stability and control requirements of airplanes are outdated because of the expansion of flight envelopes, the increase in airplane size, and the utilization of complex stability and control augmentation systems. Although research is presently being conducted in an effort to remedy this situation, to date essentially no clearly defined stability requirements and criteria have been established for very large conventional or unconventional cargo transports. Therefore, in an effort to aid in the future establishment of new stability requirements, the low-speed handling qualities parameters of a very large conventional transport, a span-loader transport, and multibody transport configurations are compared with some existing handling qualities criteria.

These transport concepts differ from current large airplanes in at least two features that can be expected to have significant effects on handling qualities, especially during the approach and landing phase. First, there is the higher gross weight (more than double that of the Lockheed C-5A) and the related increased dimensions of such items as the wing span for all concepts, the landing-gear track for the multibody and span-loader concepts, and the cockpit location for the twin-fuselage concept. Second, the magnitude of the inertias (for all configurations) and the inertia distribution (for all concepts except the very large single-fuselage configuration) are considerably different from those of conventional design and can be expected to have a meaningful impact on control requirements during landing approach.

Piloted simulation studies offer a means of obtaining preliminary handling qualities evaluations of diverse airplane concepts and assessing the adequacy of current handling qualities requirements. A previous piloted simulation study of a large multibody design with augmented stability and control characteristics, reported in reference 1, compared the resulting handling qualities with those of a large single-fuselage transport configuration that was similar to the Lockheed C-5A airplane and assessed the adequacy of current handling qualities requirements. The present paper will also utilize the "pseudo" C-5A as the reference configuration.

The primary objectives of this simulation study, using a six-degree-of-freedom, ground-based simulator, were to evaluate the low-speed handling characteristics of several additional dissimilar large-transport concepts and to obtain adequate information to provide guidance for future research requirements. Other major objectives were as follows:

(1) Compare the low-speed dynamic stability and con-

trol characteristics of the subject cargo transports with those of a large reference transport configuration. (The reference airplane was similar to the Lockheed C-5A.)

(2) Develop the augmentation systems necessary to produce satisfactory handling qualities.

(3) Evaluate the effects of various atmospheric conditions on the ability of the pilot to make a satisfactory approach and landing.

Symbols

Measurements and calculations were made in U.S. Customary Units, and all calculations are based on the airplane body axes. Dots over symbols denote differentiation with respect to time.

a_n	normal acceleration, g units
C_{L_α}	lift-curve slope per unit angle of attack, per radian
$\bar{c}$	mean aerodynamic chord, ft
g	acceleration due to gravity ($1g = 32.152$ ft/sec^2)
h	altitude, ft
I_X, I_Y, I_Z	moments of inertia about X, Y, and Z body axes, respectively, slug-ft^2
I_{XZ}	product of inertia, slug-ft^2
K_A	autothrottle gain, deg/knot
K_p	roll-rate gain, $\frac{\text{deg}}{\text{deg/sec}}$
$K_{p,c}$	commanded roll-rate gain, $\frac{\text{deg/sec}}{\text{deg}}$
$K_{p,I}$	roll-rate-integrator gain, deg/deg
$K_{p,Y}$	roll-rate gain in yaw axis, $\frac{\text{deg}}{\text{deg/sec}}$
K_q	pitch-rate gain, $\frac{\text{deg}}{\text{deg/sec}}$
$K_{q,c}$	commanded pitch-rate gain, $\frac{\text{deg/sec}}{\text{in.}}$
$K_{q,I}$	pitch-rate-integrator gain, $\frac{\text{deg/sec}}{\text{deg/sec}}$
K_r	yaw-rate gain, $\frac{\text{deg}}{\text{deg/sec}}$
K_V	autothrottle velocity gain, deg/deg
$K_{V,I}$	autothrottle velocity-integrator gain, per second
K_{WL}	wing-leveler gain, deg/deg
K_β	sideslip gain, deg/deg
$K_{\delta c}$	column-to-elevator gearing, deg/in.
$K_{\delta p}$	pedal-to-rudder gearing, deg/in.
$K_{\delta w}$	wheel-to-aileron gearing, deg/deg
K_θ	pitch-attitude gain, deg/deg
$K_{\theta,A}$	autothrottle pitch-attitude gain, deg/deg
$K_{\theta,H}$	pitch-attitude-hold gain, $\frac{\text{deg/sec}}{\text{deg/sec}}$
$K_{\phi,2}$	roll-attitude-hold gain, deg/deg
$K_{\phi,\text{TC}}$	roll-attitude-hold filter gain, per second
$K_{\phi,R}$	roll-coordination gain, deg/deg
L_α	lift per unit angle of attack per unit momentum, $(\bar{q}S/mV)C_{L_\alpha}$, per second
$L_{\delta a}$	dimensional roll-due-to-aileron-control derivative (right roll positive), per second^2
m	airplane mass, slugs
n/α	steady-state normal-acceleration change per unit change in angle of attack for an incremental horizontal-tail deflection at constant airspeed, g units/rad
P	period, sec
P_d	period of Dutch roll oscillation, sec
P_{ph}	period of longitudinal phugoid oscillation, sec
P_{sp}	period of longitudinal short-period oscillation, sec
p, r	rolling and yawing angular velocities, respectively, deg/sec
p_1, p_2	roll rates at first and second peaks, respectively, deg/sec
$\bar{q}$	dynamic pressure, lbf/ft^2
S	reference wing area, ft^2
s	Laplace operator
T	thrust, lbf
t_2	time required to double amplitude, sec
t_{s2}	time required for spiral mode to double amplitude, sec
$\text{t}_{\phi=30}$	time required to bank 30°, sec
t_1	intersection of pitch-rate-response maximum-slope tangent line and zero amplitude line (effective time delay), sec
t_2	intersection of pitch-rate-response maximum-slope tangent line and steady-state pitch-rate line, sec
Δt	effective rise time parameter, $t_2 - t_1$, sec

V indicated airspeed, knots

V_s stall speed, knots

W airplane weight, lbf

X, Y, Z longitudinal, lateral, and normal airplane axes, respectively

β angle of sideslip, deg

γ flight-path angle, deg

Δ increment

δ_a aileron deflection, positive for right roll command, deg

δ_c column deflection, in.

δ_e elevator deflection, deg

δ_f trailing-edge flap deflection, deg

δ_h horizontal-tail deflection, deg

δ_p pedal deflection, in.

δ_r rudder deflection, deg

δ_s spoiler deflection, deg

δ_w control-wheel deflection, deg

$\delta_{w,\mathrm{eff}}$ effective control-wheel deflection, wheel deflection for maximum rolling moment, deg

ζ damping ratio

ζ_d Dutch roll mode damping ratio

ζ_{ph} longitudinal phugoid-mode damping ratio

ζ_{sp} longitudinal short-period-mode damping ratio

ζ_ϕ damping ratio of numerator quadratic ϕ/δ_a transfer function

θ pitch attitude, deg

θ_o initial trim (reference) pitch attitude, deg

$\Delta\dot{\theta}_1$ magnitude of first pitch-rate overshoot, deg/sec

$\Delta\dot{\theta}_2$ magnitude of first pitch-rate undershoot, deg/sec

$\Delta\dot{\theta}_2/\Delta\dot{\theta}_1$ transient peak ratio

κ ratio of commanded roll performance to applicable roll-performance requirement

$\tau_{p,\mathrm{eff}}$ effective pitch time constant (time required to reach 63 percent of steady-state pitch rate following a step control input), sec

τ_R roll-mode time constant (from the characteristic equation of motion), sec

$\tau_{R,\mathrm{eff}}$ effective roll-mode time constant (time required to reach 63 percent of steady-state roll rate following a step control input), sec

τ_{servo} time constant of servo, sec

ϕ angle of roll, deg

$\phi_{1,\mathrm{max}}$ angle of roll in first second following a maximum lateral control input, deg

ψ heading angle, deg

ψ_β phase angle expressed as a lag for a cosine representation of Dutch roll oscillation in sideslip, deg

ω frequency, rad/sec

ω_d undamped natural frequency of Dutch roll mode, rad/sec

ω_{ph} undamped natural frequency of phugoid mode, rad/sec

ω_{sp} longitudinal short-period undamped natural frequency, rad/sec

ω_ϕ undamped natural frequency appearing in numerator quadratic of ϕ/δ_a transfer function, rad/sec

Subscripts:

app approach

av average

H hold

ℓ landing

max maximum; for attitude responses, maximum control input was used

osc oscillatory

RAH roll-attitude-hold mode on

ra roll actuator

ref reference

reqd required

rs roll spiral

ss steady state

WL wing-leveler mode on

Abbreviations:

DQ(PIL) pilot-commanded pitch rate

DWN down

FAA Federal Aviation Administration

IFR	instrument flight rules
ILS	instrument landing system
KIAS	knots of indicated airspeed (used with V_ℓ)
LDG	landing gear
PLA	power-lever angle
PR	pilot rating
RAH	roll-attitude-hold mode on
SAS	stability augmentation system
SCAS	stability and control augmentation system
VFR	visual flight rules
VLDS	visual landing display system
VMS	Langley Visual/Motion Simulator
WL	wing-leveler mode on

Description of Simulated Airplanes

Three-view sketches of the transports studied are presented in figure 1; and the representative mass properties and dimensional characteristics, as well as the control-surface deflection and deflection-rate limits, are presented in table I. The aerodynamic data used in this study were taken from appendix E of reference 2. A three-view sketch of the reference airplane is presented in figure 2, and the mass properties and dimensional characteristics are presented in table I. The aerodynamic inputs for the reference airplane were taken from table III of reference 1. An example of the estimated engine-thrust response characteristics used in the simulation is presented in figure 3.

Very Large Airplanes

The various turbojet cargo transports simulated in this study were developed by the Lockheed-Georgia Company (under a NASA contract); and, with the exception of the span loader, they were designed to carry 350 tons of payload 3500 n.mi. at a Mach number of 0.8 and an initial cruise altitude of 32 000 ft. These configurations were required to meet an FAA takeoff field length of 10 500 ft and a second-segment climb gradient of 0.03. The span-loader concept, taken from a previous Lockheed investigation, was included to study problems that may be configuration dependent as well as size dependent; it was developed to carry 273 tons of payload 3000 n.mi. at a Mach number of 0.75 and an initial cruise altitude of 35 000 ft. This configuration was required to meet an FAA takeoff field length of 7000 ft and a second-segment climb gradient of 0.03.

Single-fuselage airplane. The single-fuselage airplane was powered by six large, advanced turbofan engines providing a static takeoff thrust-to-weight ratio of 0.200. A three-view sketch of the airplane is presented in figure 1(a), and the simulated representative mass properties and dimensional characteristics are presented in table I(a).

Twin-fuselage airplane. The twin-fuselage airplane was powered by six large, advanced turbojet engines providing a static takeoff thrust-to-weight ratio of 0.185. A three-view sketch is presented in figure 1(b), and the simulated representative mass properties and dimensional characteristics are presented in table I(b).

Triple-fuselage airplane. The triple-fuselage airplane was powered by six large, advanced turbojet engines providing a static takeoff thrust-to-weight ratio of 0.195. A three-view sketch is presented in figure 1(c), and the simulated representative mass properties and dimensional characteristics are presented in table I(c).

Span-loader airplane. The span-loader airplane was powered by six large, advanced turbojet engines providing a static takeoff thrust-to-weight ratio of 0.216. A three-view sketch is presented in figure 1(d), and the simulated representative mass properties and dimensional characteristics are presented in table I(d).

Reference Airplane

A single-fuselage turbojet cargo transport, similar to the Lockheed C-5A airplane, was simulated during this study to provide a reference base from which the various large transport concepts could be evaluated. This reference airplane was powered by four turbojet engines providing a static takeoff thrust-to-weight ratio of 0.213. A three-view sketch of the airplane is presented in figure 2, and the simulated representative mass properties and dimensional characteristics are presented in table I(e).

Description of Simulation Equipment

The simulation study of the various airplane concepts was made by using the general-purpose cockpit of the Langley Visual/Motion Simulator (VMS), which is a ground-based motion simulator with six degrees of freedom. For this study it had a transport-type cockpit that was equipped with conventional flight and engine-thrust controls and with a flight-instrument display panel representative of those found in current transport airplanes. (See fig. 4.) Instruments that indicated angle of attack, angle of sideslip, and flap angle were also provided. A conventional cross-pointer-type flight-director

instrument was used, the command bars (cross pointers) being modeled to be compatible with a microwave landing system.

The control forces on the wheel, column, and rudder pedals were provided by a hydraulic system coupled with an analog computer. The system allows for the usual variable-feel characteristics of stiffness, damping, coulomb friction, breakout forces, detents, and inertia. The cockpit control displacements for the column, control wheel, and pedals are ± 7.0 in., $\pm 60^\circ$, and ± 2.5 in., respectively. The power-lever-angle (throttle) range is from 0° (maximum reverse thrust) to 58.77° (maximum thrust).

The airport-scene display used an "out-the-window" virtual-image system of the beam-splitter, reflective-mirror type. (See ref. 3.)

The motion performance characteristics of the VMS system possess time lags of less than 60 msec. A nonstandard washout system, utilizing nonlinear coordinated adaptive motion, was used to present the motion-cue commands to the motion base. (See ref. 4.)

A runway "model" was programmed that had a maximum width of 267 ft, a total length of 11 500 ft, roughness characteristics, and a slope from the center to the edge representing a runway crown. Only a dry runway was considered in this study.

The only aural cues provided were engine noises and landing-gear extension and retraction noises.

Tests and Procedures

Two research pilots participated in the simulation program. Both pilots have extensive evaluation experience in research simulation investigations. Additionally, both have flight-test experience in many types of aircraft including large transports. One pilot has over 7500 flight hours, with 2400 hr in transports; the other pilot has over 4400 flight hours, with over 2000 hr in transports. Each flew all-simulated configurations and tasks, and each used standard flight-test procedures in the evaluation of the handling and ride qualities. The primary piloting task was the approach and landing operation. The tests consisted of IFR and simulated VFR landing approaches for various configurations—with crosswinds, turbulence, wind shear, glide-slope offsets, a sidestep maneuver, and engine failure as added complicating factors. The ILS approach was initiated with the airplane in the power-approach condition (power for level flight), at an altitude below the glide slope, and on a course parallel to but offset from the localizer. The pilot's task was to capture the localizer and glide slope and to maintain them as closely as possible while under simulated IFR conditions. At an altitude of approximately 300 ft, the airplane "broke out" of the simulated overcast, whereupon the pilot converted to VFR conditions and attempted to land the airplane visually (with limited reference to the flight instruments).

This study, using the aforementioned evaluation procedures, evaluated handling qualities by analysis of recorded airplane-motion time histories, by calculation of various flying qualities parameters, and by review of pilot comments on the flying qualities of the simulated large cargo transports and on the effects of various stability and control augmentation systems on these characteristics. The more significant results are reviewed in the following sections.

Results and Discussion

The results of this study are discussed in terms of the previously stated objectives, and the pilot ratings listed for the various conditions evaluated are an average of the ratings from both pilots who flew that particular condition. (There was never more than one Cooper-Harper pilot rating difference between the pilots' assessment of the tasks.) Pilot ratings represent those given for the landing task since it was the most demanding. The pilots flew the reference transport only in the augmented mode. See table II for the pilot rating system used for handling qualities and table III for the turbulence-effect rating scale.

Without Stability Augmentation

Longitudinal characteristics. The following paragraphs present the static and dynamic stability and control characteristics of the unaugmented transports. (These characteristics are described in tables IV and V and in fig. 5.)

Single-fuselage airplane: The average pilot rating assigned to the longitudinal handling qualities of the unaugmented large single-fuselage airplane was 4.25, the primary objections being (1) sluggish initial pitch response, and (2) nonprecise attitude control due to pitch-attitude excursions associated with thrust changes.

The static longitudinal stability of the subject single-fuselage transport airplane was considered by the pilots to be acceptable, but not satisfactory. (The airplane had a negative static margin of 1 percent.) This configuration was flown on the stable side (front side) of the thrust-required curve, the variation of thrust required with velocity $\partial(T/W)/\partial V$ was approximately 0.00031 per knot, and speed control was not difficult.

The dynamic stability characteristics of this single-fuselage configuration, for the approach and landing flight conditions, are indicated in table IV(a). As can be seen, the short-period characteristics of the single-fuselage transport airplane are aperiodic and can, therefore, be compared with the t_2 criterion of reference 5. Note from table IV(a) that the approach and landing

flight conditions have a t_2 of approximately 48 and 54 sec, respectively. The acceptable average PR of 4.25 agrees with the referenced criterion in that t_2 was much greater than 6 sec, the minimum allowable for acceptable handling qualities.

The pilots commented that the initial pitch response to column inputs was sluggish. This sluggish response, caused by the high pitch inertia, is illustrated in figure 5(a), which presents the pitch-rate response to a column step input calculated from two-degree-of-freedom equations of motion with airspeed constrained. By using the pitch-rate response criteria of reference 6, figure 5(a) indicates that the reason the pilots rated the pitch response as being sluggish was the magnitude of the "rise time parameter." The reference 6 criterion dictates that the pitch-rate rise time parameter Δt of the simulated single-fuselage configuration must be less than 0.83 sec for a satisfactory response (level 1) and less than 2.67 sec for an acceptable response (level 2). As noted in table V(a) and figure 5(a), the pitch-rate rise time parameter for the unaugmented single-fuselage transport was 2.57 sec, which predicts acceptable, but not satisfactory, pitch-rate response characteristics; this agrees with the pilot rating of 4.25 determined on the simulator. The pitch control power was rated acceptable insofar as the longitudinal control-power requirements for the approach and landing tasks are concerned. This is in agreement with the control-power-requirements criterion of reference 7, as shown in figure 6. Therefore, stability and control augmentation would be required to achieve satisfactory handling qualities for the approach and landing piloting tasks. Also note from table V(e) that the pitch-rate rise time parameter for the reference airplane was acceptable, but not satisfactory, when compared with the reference 6 criterion.

Twin-fuselage airplane: The average pilot rating assigned to the longitudinal handling qualities of the unaugmented twin-fuselage airplane was 4.5, the primary objections being (1) sluggish initial pitch response, and (2) nonprecise attitude control due to large changes in pitch attitude caused by thrust variations and/or trailing-edge flap movement.

The static longitudinal stability of the subject twin-fuselage transport airplane was considered by the pilots to be adequate. (The airplane had a static margin of 1 percent.) Also, this configuration was flown on the stable side (front side) of the thrust-required curve with $\partial(T/W)/\partial V = 0.00020$ per knot.

Figure 7 presents two of the most widely used longitudinal handling qualities criteria. Figure 7(a) shows the short-period frequency requirement of reference 8, and figure 7(b) shows the Shomber-Gertsen longitudinal handling qualities criterion of reference 9. The reference 9 criterion relates the ability of the pilot to change flight path (using normal acceleration) to the factor L_α. By using this parameter and by recognizing that the pilot's mode of control is not constant for all flight regimes, a criterion for satisfactory short-period characteristics was developed (ref. 9) that correlates well with current airplane experience. The dynamic stability characteristics of this configuration, for the approach and landing, are indicated in table IV(b); the control-response characteristics are indicated in table V(b) and figure 5(b); and some dynamic parameters are compared with some present-day transports in figure 7. Again, the pilots commented that the initial pitch response to column inputs was sluggish, as illustrated in figure 5(b). Note that the rise time parameter is 2.45 sec, which is greater than the satisfactory-response requirement of 0.88 sec but less than the acceptable-response requirement of 2.84 sec. As noted in table V(b) and figure 5(b), the pitch-rate response characteristics are predicted as acceptable, but not satisfactory. This agrees with the pilot rating of 4.5 determined on the simulator. The pitch control power was rated acceptable insofar as the longitudinal control-power requirements for the approach and landing tasks are concerned. (See fig. 6.) Therefore, stability and control augmentation would be required to achieve satisfactory longitudinal handling qualities for the approach and landing piloting tasks.

Triple-fuselage airplane: The average pilot rating assigned to the longitudinal handling qualities of the unaugmented triple-fuselage airplane was 2.25, indicating satisfactory handling qualities.

The static longitudinal stability of the subject triple-fuselage transport airplane was considered by the pilots to be adequate. (The airplane had a static margin of 5 percent.) Also, this configuration was flown on the stable side (front side) of the thrust-required curve with $\partial(T/W)/\partial V = 0.00031$ per knot.

The dynamic stability characteristics of this configuration, for the approach and landing, are indicated in table IV(c); the control-response characteristics are indicated in table V(c) and figure 5(c); and some dynamic parameters are compared with some present-day transports in figure 7. Although the pilots evaluated the pitch response as being satisfactory, it can be seen from figure 5(c) and table V(c) that the effective rise time parameter of this unaugmented configuration was 1.23 sec, which is greater than the parameter that the reference 6 criterion allows for satisfactory-response characteristics. The pitch control power was rated acceptable insofar as the longitudinal control-power requirements for the approach and landing tasks are concerned. (See fig. 6.) Therefore, stability and control augmentation would be required to achieve a satisfactory "effective rise time parameter" for the approach and landing piloting tasks.

Span-loader airplane: The average pilot rating as-

signed to the longitudinal handling qualities of the unaugmented span-loader airplane was 5.5, the primary objections being (1) slightly sluggish initial pitch response, (2) low control power, (3) nonprecise attitude control due to large changes in pitch attitude associated with thrust changes, and (4) poor trimmability.

The static longitudinal stability of the subject span-loader transport airplane was considered by the pilots to be adequate. (The airplane had a static margin of 7 percent.) Also, this configuration was flown on the stable side (front side) of the thrust-required curve with $\partial(T/W)/\partial V = 0.00031$ per knot.

The longitudinal dynamic stability characteristics of this configuration, for the approach and landing, are indicated in table IV(d); the control-response characteristics are indicated in table V(d) and figure 5(d); and some dynamic parameters are compared with some present-day transports in figure 7. The pilots commented that the initial pitch response was slightly sluggish, as illustrated in figure 5(d). Note that the rise time parameter is 1.10 sec, as compared with the satisfactory-response requirement of less than 0.96 sec and the acceptable-response requirement of less than 3.09 sec. (See table V(d).) As noted in table V(d) and figure 5(d), predicted response characteristics are indicated as being acceptable, but not satisfactory, and this agrees with the pilot rating of 5.5 determined on the simulator. The pitch control power was rated unacceptable insofar as the longitudinal control-power requirements for the approach and landing tasks are concerned. This is not in agreement with the control-power-requirements criterion of reference 7, as indicated in figure 6. The large positive increment in normal acceleration is due to the pitch control surface (canard) being located ahead of the airplane center of gravity. Considerable stability and control augmentation would be required to achieve satisfactory longitudinal handling qualities for the approach and landing piloting tasks.

Lateral-directional characteristics. The following paragraphs present the stability and control characteristics of the unaugmented transports.

Single-fuselage airplane: A pilot rating of 4.0 was assigned to the lateral-directional handling qualities of the unaugmented single-fuselage airplane. The major objections were (1) relatively sluggish roll response, (2) difficulty in coordinating turns due to sideslip oscillations caused by wheel inputs, and (3) a large amount of adverse sideslip.

One primary factor that contributed to the acceptable, but not satisfactory, pilot rating for the lateral-directional characteristics was the large adverse sideslip experienced during rolling maneuvers, and this characteristic is indicated in figure 8(a). For a step wheel input, it is desirable to have (1) a rapid roll-rate response that reaches a reasonable steady-state value with a minimum of oscillation, (2) essentially zero sideslip produced by the control input, and (3) an immediate response in heading. However, it is evident from figure 8(a) that for a lateral-control step wheel input for this unaugmented configuration, a large amount of adverse sideslip is experienced that washes out the roll rate $\dot{\phi}$. In addition, table V(a) indicates that it takes approximately 3.3 sec to bank 30° on this unaugmented airplane in the landing configuration and that the requirement of reference 8 is $t_{\phi=30} \leq 2.5$ sec for satisfactory handling qualities. Therefore, stability and control augmentation would be required to achieve satisfactory handling qualities for the approach and landing piloting task.

Twin-fuselage airplane: The average pilot rating of 5.5 was assigned to the lateral-directional handling qualities of the unaugmented twin-fuselage airplane. The major objections were (1) sluggish roll response, (2) difficulty in coordinating turns due to large sideslip excursions caused by wheel inputs, and (3) the requirement to hold pedal force constantly in turns.

One primary factor that contributed to the less-than-satisfactory pilot rating for the lateral-directional characteristics was the adverse sideslip experienced during rolling maneuvers, as illustrated in figure 8(b). This adverse sideslip washes out the roll rate $\dot{\phi}$. In addition, table V(b) indicates that it takes more than 5 sec to bank 30° on this unaugmented airplane in the landing configuration and that the requirement of reference 8 is $t_{\phi=30} \leq 4$ sec, even for acceptable handling qualities. It was therefore apparent that stability and control augmentation would be required to achieve satisfactory lateral-directional handling qualities for the approach and landing piloting task.

Triple-fuselage airplane: The average pilot rating of 4.0 was assigned to the lateral-directional handling qualities of the unaugmented triple-fuselage airplane. The major objections were (1) sluggish roll response, and (2) difficulty in coordinating turns due to large sideslip excursions caused by wheel inputs.

One primary factor that contributed to the less-than-satisfactory pilot rating for the lateral-directional characteristics was the adverse sideslip experienced during rolling maneuvers which washes out the roll rate $\dot{\phi}$. (See fig. 8(c).) In addition, table V(c) indicates that it takes approximately 5 sec to bank 30° in this unaugmented airplane in the landing configuration and that the requirement of reference 8 is $t_{\phi=30} \leq 4$ sec, even for acceptable handling qualities. It was therefore apparent that stability and control augmentation would be required to achieve satisfactory lateral-directional handling qualities for the approach and landing piloting task.

Span-loader airplane: The average pilot rating of 6.5 was assigned to the lateral-directional handling qualities of the unaugmented span-loader airplane. The major objections were (1) sluggish roll response, (2) difficulty in coordinating turns due to large sideslip excursions caused by wheel inputs, and (3) low Dutch roll damping.

Two primary factors that contributed to the marginally acceptable pilot rating for the lateral-directional characteristics were the adverse sideslip experienced during rolling maneuvers which washes out the roll rate $\dot{\phi}$ and the low Dutch roll damping. (See fig. 8(d) and table IV(d), respectively.) In addition, table V(d) indicates that it takes approximately 6 sec to bank 30° in this unaugmented airplane in the landing configuration and that the requirement of reference 8 is $t_{\phi=30} \leq 4$ sec, even for acceptable handling qualities. It was therefore apparent that stability and control augmentation would be required to achieve satisfactory lateral-directional handling qualities for the approach and landing piloting task.

Augmented Airplane

Based on the results obtained for the unaugmented configuration, the objective for the design of the stability and control augmentation system (SCAS) was that the system should provide satisfactory handling qualities (PR $\leq$ 3.5) at all flight conditions evaluated during the study. Recent experience with handling qualities simulation studies has shown a pilot preference for use of rate-command/attitude-hold control systems in the longitudinal and lateral axes. Nominal control-system gains were selected by calculating the longitudinal and lateral-directional dynamic stability characteristics of the airplane (including the complete control system) by utilizing linear three-degree-of-freedom equations of motion and aerodynamics. The airplane and control system were then programmed for six-degree-of-freedom piloted simulation with nonlinear aerodynamics. The airplane and control system were then programmed for six-degree-of-freedom real-time simulation. By using control steps, pulses, and doublets, the responses were tailored by gain modifications. Final control-system and stability-augmentation gains were selected when the airplane was flown on the VMS/VLDS. A block diagram of the SCAS design obtained is shown in figure 9. (The δ_a output of the lateral control system (fig. 9(b)) includes spoiler deflection.) The selected gains for the pitch-, roll-, and yaw-axes SCAS are indicated in table VI.

It may be noted from tables IV(b) to IV(d) that a coupled roll-spiral mode is present for the augmented configurations. This mode was determined by analyses of the linear quasistatic lateral-directional characteristic equations, including the stability and control augmentation systems; but it was not detected by the pilots while flying the simulator. It may also be noted from table IV(a) that the coupled mode is a roll-aileron actuator mode, as opposed to a coupled roll-spiral mode. Again, this mode was not detected by the pilots.

Longitudinally, a high-gain pitch-rate-command/attitude-hold system was chosen because (1) the system provided good short-period characteristics and rapid response to pilot inputs, and (2) the attitude-hold feature minimized disturbances due to turbulence or variations in flaps and/or thrust.

Laterally, a roll-rate-command/attitude-hold system was employed in an attempt to provide a rapid roll mode and quick uniform response to pilot inputs; the attitude-hold feature resulted in a desirable neutrally stable spiral mode while counteracting disturbances due to turbulence. In addition, a wings-leveler feature was provided which automatically leveled the wings ($\phi = 0°$) whenever the bank angle was less than 2° and the wheel was centered. This feature relieved the pilot of the task of "hunting" for zero bank angle and was particularly useful when rolling out of a turn to a desired heading. (See fig. 9(b) for the lateral control system.)

Directionally, roll-rate and roll-attitude feedbacks were used to provide turn coordination and improved Dutch roll characteristics. Additional feedbacks of yaw rate and sideslip were used on the very large single-fuselage transport airplane to increase Dutch roll undamped natural frequency and to counteract the large adverse sideslip exhibited by this configuration. (See fig. 9(c).)

An autothrottle that maintained the selected airspeed throughout the landing approach was also used as part of the normal operational augmentation. (See fig. 10 for a block diagram of the autothrottle design.) Since the simulated engine dynamics (e.g., see fig. 3) produced very good thrust response, the autothrottle generally maintained the desired airspeed within ±3 knots and considerably reduced the pilot workload on the landing approach.

Longitudinal characteristics. The longitudinal SCAS (fig. 9(a)) provided a pitch rate proportional to column deflection and produced the desired characteristics of rapid well-damped responses to pilot inputs, as well as inherent attitude stability. The pitch-rate response characteristics are presented in figure 11; and the dynamic stability and control characteristics are compared with some existing flying qualities criteria in figures 12 and 13.

Single-fuselage airplane: Figure 11(a) shows the improvement in pitch-rate response provided by the SCAS and also compares the pitch response of the single-fuselage transport with the reference airplane. As can be seen, the SCAS improved the pitch-rate response of

the single-fuselage configuration appreciably in that the pitch time constant was decreased by 67 percent ($\tau_{p,\mathrm{eff}}$ decreased from 2.41 to 0.79 sec) and the steady-state pitch rate commanded by a given column input was increased by 20 percent to the desired rate of 1.50 deg/sec, determined by the evaluation pilots. It may also be noted that the pitch-rate response of the augmented single-fuselage configuration compares favorably with the augmented reference airplane. With the augmentation system operative, the average pilot rating for the longitudinal handling qualities during the ILS approach was improved from 4.25 to 2.5.

Figure 12 compares these configurations with the short-period handling qualities criteria of references 8 and 9; and, as can be seen, the single-fuselage configuration agrees quite well with both criteria since the augmented configuration is in the satisfactory region.

The low-speed pitch-rate response criterion shown in figure 13(a), and reported in reference 10, was based on the Shomber-Gertsen criterion of reference 9. Indications are that the single-fuselage configuration does not meet the pitch-rate response requirements of this criterion, even when the airplane is highly augmented. (Also note that the simulated reference airplane does not meet this criterion.) However, when the pitch-rate response of the augmented single-fuselage configuration is compared with the criteria of reference 6, it can be seen from figure 14(a) and table V(a) that the predicted characteristics were at satisfactory levels for effective time delay and transient peak ratio, but at only an acceptable level when the rise time parameter Δt is considered. It should be noted from table V(a), however, that the augmented Δt essentially agrees with the reference 6 criterion in that $\Delta t = 0.99$ sec, compared with a maximum allowed value of 0.83 sec.

Twin-fuselage airplane: The improvement in pitch-rate response provided by the SCAS of the twin-fuselage transport can be seen in figure 11(b) indicating a decrease in pitch time constant of 78 percent ($\tau_{p,\mathrm{eff}}$ decreased from 2.43 to 0.65 sec). With the augmentation system operative, the average pilot rating for the longitudinal handling qualities during the ILS approach was improved from 4.5 to 2.0.

A comparison of the twin-fuselage-transport short-period characteristics with the handling qualities criteria of references 8 and 9 (fig. 12) indicates satisfactory characteristics for the augmented configuration and is in agreement with the pilots' assessment.

The low-speed pitch-rate response criterion (ref. 10) shown in figure 13(b) indicates that the augmented twin-fuselage transport does not meet the pitch-rate response requirements of this criterion. However, when the pitch-rate response of the augmented twin-fuselage configuration is compared with the criterion of reference 6, it can be seen from figure 14(b) and table V(b) that the predicted characteristics were at satisfactory levels and in agreement with the pilots' assessment of the configuration.

Triple-fuselage airplane: Figure 11(c) shows the improvement in pitch-rate response provided by the SCAS of the triple-fuselage transport as seen by a decrease of 55 percent in pitch time constant ($\tau_{p,\mathrm{eff}}$ decreased from 0.94 to 0.40 sec) and by a decrease of 20 percent in commanded steady-state pitch rate to the desired rate of 1.50 deg/sec. With the augmentation system operative, the average pilot rating for the longitudinal handling qualities during the ILS approach was improved from 2.25 to 1.0.

Figure 12 compares the configuration with the short-period handling qualities criteria of references 8 and 9; as can be seen, the triple-fuselage configuration can be said to agree with the short-period frequency criterion of reference 8 but not with the handling qualities criterion of reference 9, suggesting a possible modification of the lower satisfactory boundary.

The low-speed pitch-rate response criterion (ref. 10) shown in figure 13(c) indicates that the augmented triple-fuselage transport meets the pitch-rate response requirement. Also, when compared with the criteria of reference 6, it can be seen from figure 14(c) and table V(c) that the predicted characteristics were at satisfactory levels and in agreement with the pilots' assessment of the configuration.

Span-loader airplane: The improvement in pitch-rate response provided by the SCAS of the span-loader transport can be seen in figure 11(d) to be an increase of 425 percent to the desired commanded steady-state pitch rate of 2.50 deg/sec (determined by the evaluation pilots) for this configuration. With the augmentation system operative, the average pilot rating for the longitudinal handling qualities during the ILS approach was improved from 5.5 to 2.25.

A comparison of the short-period characteristics of the span-loader transport with the handling qualities criteria of references 8 and 9 (fig. 12) indicates satisfactory characteristics for the augmented configuration and is in agreement with the pilots' assessment.

The low-speed pitch-rate response criterion (ref. 10) shown in figure 13(d) indicates that the augmented span-loader transport does not meet the pitch-rate response requirements of this criterion. Also, when the pitch-rate response of the augmented span-loader configuration is compared with the criteria of reference 6, it can be seen from figure 14(d) and table V(d) that the predicted characteristics were unacceptable for effective time delay, acceptable for rise time parameters, and satisfactory for transient peak ratio, which is not in agreement with the pilots' assessment of the configuration.

Lateral-directional characteristics. A block diagram of the lateral-directional SCAS is presented in figure 9. Laterally, a rate command system provided roll rate proportional to wheel position (fig. 9(b)), and the directional system consisted of two or more turn-coordination features (fig. 9(c)). Only the single-fuselage configuration required more than two turn-coordination features.

Single-fuselage airplane: Table IV(a) shows that the Dutch roll characteristics of the single-fuselage transport were improved considerably, ω_ϕ/ω_d was increased from 0.873 to 0.998 (which indicates that the Dutch roll oscillation should be much less easily excited for roll-control inputs), and the damping parameter $\zeta_d\omega_d$ was increased from 0.033 to 0.108 rad/sec. The improvement in the roll response and damping is indicated by the reduction of roll time constant from 1.12 to 0.42 sec.

Figure 15(a) shows the improvement in the roll-rate response of the single-fuselage transport provided by the SCAS. By elimination of the large adverse sideslip, the final roll rate attained for a given amount of wheel deflection was maintained constant, and the heading response was improved. A comparison of the lateral-directional response to a wheel step for the augmented single-fuselage airplane and the simulated reference airplane indicates that the initial roll-rate response of the single-fuselage airplane is faster than the ϕ response of the reference airplane. Indications are that the sideslip β and heading response ψ of the two configurations are similar. (See fig. 15(a).)

With the SCAS operative, the average pilot rating for the lateral-directional handling qualities on the ILS approach in calm air was improved from 4.0 to 2.75.

The roll-rate response characteristics presented in tables IV(a) and V(a) indicate that (1) the effective time delay would be expected to be at a satisfactory level since $t_1 < 0.283$ sec, (2) the roll-mode time constant would be expected to be at a satisfactory level since it was less than 1.4 sec, and (3) the time required to bank 30° would be expected to be at an acceptable level since $t_{\phi=30} \leq 4$ sec.

Twin-fuselage airplane: Table IV(b) shows that the Dutch roll characteristics of the twin-fuselage transport were improved considerably, ω_ϕ/ω_d was increased from 0.791 to 1.000, and the damping parameter $\zeta_d\omega_d$ was increased from 0.029 to 0.063 rad/sec. The improvement in the roll response and damping is indicated by the reduction of roll-mode time constant from 1.58 to 0.69 sec.

Figure 15(b) shows the improvement in the roll-rate response of the twin-fuselage transport provided by the SCAS. By elimination of the large adverse sideslip, the roll rate attained for a given wheel deflection was increased appreciably, and the heading response was immediate (no lag). A comparison of the lateral-directional response to a wheel step for the augmented twin-fuselage airplane and the simulated reference airplane indicates that the large twin-fuselage configuration had the more desirable characteristics.

With the SCAS operative, the average pilot rating for the lateral-directional handling qualities on the ILS approach in calm air was improved from 5.5 to 2.0.

The roll-rate response characteristics presented in tables IV(b) and V(b) indicate that (1) the effective time delay would be expected to be at a satisfactory level since $t_1 < 0.283$ sec, (2) the roll-mode time constant would be expected to be at a satisfactory level since it was less than 1.4 sec, and (3) the time required to bank 30° would be expected to be at an unacceptable level since $t_{\phi=30} > 4$ sec. However, as stated previously, the roll response of the augmented configuration was rated as satisfactory (PR = 2.0).

Triple-fuselage airplane: Table IV(c) shows that the Dutch roll characteristics of the triple-fuselage transport were improved considerably, ω_ϕ/ω_d was increased from 0.848 to 0.999, and the damping parameter $\zeta_d\omega_d$ was increased from 0.049 to 0.080 rad/sec. The improvement in the roll response and damping is indicated by the reduction of roll-mode time constant from 1.40 to 0.57 sec.

Figure 15(c) shows the improvement in roll-rate response of the triple-fuselage transport provided by the SCAS. By elimination of the large adverse sideslip, the roll rate attained for a given wheel deflection was increased appreciably, and the heading response was immediate (no lag). A comparison of the lateral-directional response to a step wheel input for the augmented triple-fuselage airplane and the simulated reference airplane indicates that the large triple-fuselage configuration had the more desirable characteristics. (See fig. 15(c).)

With the SCAS operative, the average pilot rating for the lateral-directional handling qualities on the ILS approach in calm air was improved from 4.0 to 2.0.

The roll-rate response characteristics presented in tables IV(c) and V(c) indicate that (1) the effective time delay would be expected to be at a satisfactory level since $t_1 < 0.283$ sec, (2) the roll-mode time constant would be expected to be at a satisfactory level since it was less than 1.4 sec, and (3) the time required to bank 30° would be expected to be at an unacceptable level since $t_{\phi=30} > 4$ sec. However, as stated previously, the roll response of the augmented configuration was rated as satisfactory (PR = 2.0).

Span-loader airplane: Table IV(d) shows that the Dutch roll characteristics of the span-loader transport were improved considerably, ω_ϕ/ω_d was increased from 0.855 to 0.997, and the damping parameter of $\zeta_d\omega_d$ was increased from 0.002 to 0.068 rad/sec. The improvement in the roll response and damping is indicated by

the reduction of roll-mode time constant from 2.33 to 0.85 sec.

Figure 15(d) shows the improvement in roll-rate response of the span-loader transport provided by the SCAS. By elimination of the large adverse sideslip, the roll rate attained for a given wheel deflection was increased appreciably, and the heading response was immediate (no lag).

With the SCAS operative, the average pilot rating for the lateral-directional handling qualities on the ILS approach in calm air was improved from 6.5 to 4.5. The primary objection of the pilots to the lateral-directional characteristics of the augmented span-loader configuration was the sluggish initial roll response.

The roll-rate response characteristics presented in tables IV(d) and V(d) indicate that (1) the effective time delay would be expected to be at an unacceptable level since $t_1 > 0.400$ sec, (2) the roll-mode time constant would be expected to be at a satisfactory level since it was less than 1.4 sec, and (3) the time required to bank 30° would be expected to be at an unacceptable level since $t_{\phi=30} > 4$ sec. However, as stated previously, the roll response of the augmented configuration was rated as acceptable but not satisfactory (PR = 4.5).

Turbulence effects. Flight in rough air was evaluated by using a turbulence model based on the Dryden spectral form. The root-mean-square value of the longitudinal, lateral, and vertical gust-velocity components was 6 ft/sec. This value was described by the pilots as being representative of moderate-to-heavy turbulence.

For all transports simulated, the pilots commented that the rating for the approach task on the augmented transports was degraded by one-half when the landing approach was made in the simulated heavy turbulence because of the increased work load required to maintain ILS tracking. By utilizing the turbulence-effect rating scale indicated in table III, both pilots assigned a rating of D on the triple-fuselage and span-loader configurations. For the single-fuselage transport, one pilot assigned a turbulence-effect rating of D and the other assigned a rating of E. For the twin-fuselage transport, one pilot assigned a turbulence-effect rating of C and the other assigned a rating of D.

Evaluation of Roll-Performance Requirements

The parameter $t_{\phi=30}$ was examined quite thoroughly during the simulation study reported in reference 1. The subject simulation-study results are also presented in the form of pilot opinion of the maximum tolerable values of $t_{\phi=30}$ for various simulated piloting tasks and are compared with the reference 1 study results.

The roll requirements of reference 8 for large, heavy, low-to-medium maneuverability airplanes—the airplane class applied to the various configurations simulated in the present study, although they are much larger than "normal" class III airplanes—are as follows for satisfactory performance:

(1) The roll-mode time constant shall be no greater than 1.4 sec.

(2) The yaw and roll control power shall be adequate to develop at least 10° of sideslip in the power-approach flight condition, with not more than 75 percent of the available roll control power.

(3) It shall be possible to land with normal pilot skill and technique in 90° crosswinds with velocities up to 30 knots.

(4) The time required to bank the airplane 30° shall not exceed 2.5 sec.

As can be seen from tables IV(a) to IV(d), the roll-mode time constant was ≤ 0.85 sec for all augmented transport concepts. These levels met the requirement of reference 4 for satisfactory performance. Note, however, that the reference transport had larger roll time constants than those required for either satisfactory or acceptable performance.

Figure 16 indicates the crosswind trim capability of all transport concepts, and it can be seen that (1) the yaw and roll control power is adequate to develop more than a 10° sideslip with 75 percent of the roll control power available, and (2) the roll and yaw control power is sufficient to trim the airplane in 90° crosswinds with velocities up to 30 knots. Therefore, the roll control power is sufficient to meet both of these reference 8 requirements.

In addition to these requirements, reference 8 dictates that the time required to bank the airplane 30° shall not exceed 2.5 sec. As can be seen from table V, all simulated augmented configurations exceed that requirement. However, the pilots rated the lateral-directional handling qualities of the large single-fuselage, twin-fuselage, and triple-fuselage transports satisfactory for the ILS approach in calm air and acceptable for the span-loader transport. Also, when performing simulated landing approaches in 90° crosswinds, the pilots rated the triple-fuselage transport satisfactory in crosswinds up to 30 knots and acceptable for the large single-fuselage and twin-fuselage transports. Only the span-loader transport was considered to be unacceptable at crosswinds greater than approximately 17 knots. (See fig. 17.)

The reference 1 study attempted to determine the maximum tolerable time required to bank the simulated large twin-fuselage transport 30° in adverse landing conditions. The landing tasks simulated included (1) an artificial ceiling of 300 ft, (2) a 200-ft lateral offset from the extended centerline of the runway (lo-

calizer beam), (3) a steady 90° crosswind of 15 knots, (4) a 16-knot, 90° horizontal crosswind shear for the last 200 ft of altitude, and (5) various combinations of these four. The results of those tests indicated that a value of $t_{\phi=30}$ less than 6 sec should result in acceptable roll-response characteristics; and when $t_{\phi=30}$ is less than 3.8 sec, satisfactory roll response should be attainable. The four large cargo transports simulated in the present study were also evaluated by utilizing the aforementioned landing tasks of reference 1 in regard to the maximum tolerable time required to bank 30°, and the pilot-opinion results are presented in figure 18. (The $t_{\phi=30}$ results of reference 1 are also indicated in fig. 18.) Notice that all simulated transports, except for the span-loader concept, were rated better than the simulated reference airplane, although the roll response ($t_{\phi=30}$) was not nearly as fast. Because the C-5A is known to be a "good flying machine," the acceptable, but unsatisfactory, pilot ratings for the reference transport at $t_{\phi=30} = 3.1$ sec were not used to define the boundary presented in reference 1. The acceptable pilot rating resulted because of directional stability characteristics that were less than ideal. The subject simulation-study results, including the span-loader results, confirm the reference 1 roll-performance conclusions: namely, for large and/or unusually configured airplanes, a value of $t_{\phi=30}$ less than 6 sec should result in acceptable roll-response characteristics and, when $t_{\phi=30}$ is less than 3.8 sec, satisfactory roll response should be attainable. (See fig. 18.)

References 11 and 12 suggest that the bank angle attained in the first second, after initiation of maximum control-wheel deflection, has a minimum value of 7° or 8° for satisfactory roll performance. (Reference 11 indicates a value of $\phi_{1,\max}$ of 8°, and ref. 12 indicates a value of 7° (PR = 3).) The reference 12 data, together with the subject simulation-study results, are presented in figure 19. Note that for PR = 3, the present simulation results indicate a $\phi_{1,\max}$ of approximately 1°, which is significantly lower than the reference 12 data. The variation of pilot rating with the maximum bank angle attained in the first second, as a function of effective control-wheel angle, is presented in figure 20. The lines of constant effective wheel angle suggest that the pilot is rating the bank-angle response per wheel deflection or roll-response sensitivity. The significance of this parameter, for the reference 13 data, is indicated by the fact that a constant pilot rating of 3 was obtained at a constant value of $\phi_{1,\max}/\delta_{w,\mathrm{eff}} = 0.1$; whereas $\phi_{1,\max}$ varied from 3° ($\delta_{w,\mathrm{eff}} = 30°$) to 90° ($\delta_{w,\mathrm{eff}} = 90°$). Note also the results of the present large-airplane simulation study: For a pilot rating of 3, $\phi_{1,\max}/\delta_{w,\mathrm{eff}}$ is also 0.1, indicating that the roll-response sensitivity (the bank angle attained in the first second per unit wheel deflection) can be correlated for a constant pilot rating for a range of effective wheel angles from 15° to 90° ($\phi_{1,\max} = 1.5°$ to 9°).

Engine Failure

During the subject study, attempts were made to simulate the go-around capabilities as well as continued approaches and landings after an outboard-engine failure on the four dissimilar cargo transport airplanes. No problems were experienced either when attempting to "continue the approach to land" or when attempting to perform a go-around.

Dynamic Stability Requirements and Criteria

As previously stated, for several years the aircraft industry has been aware that many of the existing stability and control requirements of aircraft are outdated because of the expansion of flight envelopes, the increase in airplane size, and the utilization of complex stability and control augmentation systems. Therefore, in an effort to aid in the future establishment of new stability requirements, the low-speed handling qualities parameters of an existing large reference transport, a very large conventional transport, a span-loader transport, and multibody transport configurations are compared with some existing handling qualities criteria.

Two of the most widely used longitudinal handling qualities criteria are presented in figure 12. Figure 12(a) shows the short-period frequency requirements of reference 8 and, as stated previously, the results predicted by the criterion agree with the results obtained during the present simulation studies. Figure 12(b) shows the Shomber-Gertsen longitudinal handling qualities criterion of reference 9; this criterion relates the ability of the pilot to change flight path (using normal acceleration) to the factor L_α. By using this parameter and by recognizing that the pilot's mode of control is not constant for all flight regimes, a criterion for satisfactory low-speed, short-period characteristics was developed (ref. 9) that correlates well with current airplane experience and is essentially consistent with the results of the present simulation study of very large transport airplanes.

The low-speed pitch-rate response criterion presented in figure 13, and reported in reference 10, was based on the Shomber-Gertsen criterion of reference 9. After a short time (<1.5 sec), there is excellent agreement between the results obtained during the present study and the low-speed pitch-rate response criterion. In terms of effective time delay, as defined in reference 6, the very large single-fuselage transport, the twin-fuselage transport, and the triple-fuselage transport concepts exhibit level 1 (satisfactory) characteristics, but the span-loader transport concept exhibits

a level 3 (unacceptable) effective time-delay characteristic. For the effective rise-time parameter criterion, as defined in reference 6, the very large single-fuselage and span-loader configurations do not exhibit a level 1 characteristic—each exhibits a level 2 (acceptable but unsatisfactory) characteristic. In terms of transient peak ratio, as defined in reference 6, all configurations exhibit level 1 characteristics. (See fig. 14 and table V.) These results indicate that some of the reference 6 criteria are not applicable to these very large airplanes. These results also suggest that the lower boundary of the reference 10 pitch-rate response criterion (fig. 13) should be modified for these classes of large transports.

The roll-acceleration capability criterion for transport airplanes is presented in figure 21 and reported in reference 14. The various configurations evaluated during the present simulation study are indicated in this figure and would not be considered to be in agreement with the results predicted by this criterion. Analysis of the maximum lateral-control-power data of references 12 and 15, and presented in figure 22, confirms the lower satisfactory and acceptable boundaries of figure 21. However, note that the jet transport of reference 12 is a Lockheed JetStar with a typical landing weight of approximately 30 000 lb, and the jet transport of reference 15 is a Convair 990 with a typical landing weight of approximately 150 000 lb (two widely different transport sizes). A minimum satisfactory level of lateral control power from these data is approximately 0.3 rad/sec^2, whereas the present study results and those of reference 1 indicate a minimum level of approximately 0.09 rad/sec^2. The study in reference 12 also established the required roll-acceleration capability while performing the landing offset maneuvers. These results are presented in figure 23 together with the maximum lateral-control-power results from the studies of very large airplanes. Notice, now, that the minimum satisfactory level of lateral control power has been reduced to approximately 0.12 rad/sec^2, which is much closer to the value of 0.09 rad/sec^2 required for the very large airplanes. This suggests that the lower boundaries of the roll-acceleration capability criterion of reference 14 (fig. 21) can be realistically lowered when considering very large airplanes.

The roll-rate capability criterion for transport airplanes is presented in figure 24 and reported in reference 16. The various configurations evaluated during the present simulation study are indicated in this figure and would not be considered to be in agreement with the results predicted by this criterion.

The bank-angle oscillation, roll-rate oscillation, and sideslip-excursion limitations of reference 8 are presented in figure 25. They relate the phase angle of the Dutch roll component of sideslip ψ_β to the measure of the ratio of the oscillating component to the average component of bank angle and roll rate and also to the maximum sideslip excursion. The various configurations evaluated during the present simulation study are indicated in this figure, and it can be seen that the simulated characteristics agree well with the aforementioned criteria. It should be noted that the ratio of commanded roll performance (ϕ in 2.5 sec) to applicable roll-performance ($\phi = 30°$) requirement κ was low. The resulting values of $\Delta\beta_{\max}/\kappa$ fell below the satisfactory criterion boundary because the lateral-directional stability augmentation system limited the sideslip excursion to low levels. If the commanded roll performance had been based on attaining ϕ in 3.8 sec (a suggested new requirement in the present paper for very large transports), the values of $\Delta\beta_{\max}/\kappa$ would have been even lower because of the larger value of κ resulting from increased achieved bank angle. This outcome would require that the present criterion boundaries be modified to be consistent with the way they were formulated.

In general, the results of the present simulation study agree reasonably well with the handling qualities criteria used for comparison in this paper, except for the roll-acceleration and roll-rate capability criteria of references 14 and 16. Also, it may be noted that the augmented very large transport configurations compared favorably with the reference transport.

Concluding Remarks

A six-degree-of-freedom, ground-based simulator study has been conducted to evaluate the low-speed flight characteristics of several dissimilar cargo transport airplanes and to compare these characteristics with those of a large single-fuselage (reference) transport configuration similar to the Lockheed C-5A airplane. The primary piloting task was the approach and landing operation. This paper has attempted to summarize the results of the study which support the following major concluding remarks.

The average pilot ratings assigned to the longitudinal handling qualities were 4.25, 4.5, and 5.5 (acceptable, but unsatisfactory) for the unaugmented very large single-fuselage, twin-fuselage, and span-loader transport concepts, respectively; the primary objections were (1) sluggish initial pitch response and (2) nonprecise attitude control due to large changes in pitch attitude caused by thrust variations and/or trailing-edge flap movement. The unaugmented triple-fuselage transport airplane had a satisfactory average pilot rating of 2.25.

The average pilot ratings assigned to the lateral-directional handling qualities were 4.0, 5.5, and 4.0 (acceptable, but unsatisfactory) for the unaugmented very large single-fuselage, twin-fuselage, and triple-fuselage

transport airplanes, respectively; the primary objections were (1) sluggish roll response and (2) difficulty in coordinating turns due to large sideslip excursions caused by wheel inputs. The unaugmented span-loader transport airplane had a marginally acceptable average pilot rating of 6.5; the primary objections were the same as for the other configurations and, in addition, this airplane had low Dutch roll damping.

The longitudinal stability and control augmentation system, consisting of a high-gain pitch-rate-command/attitude-hold system and an autothrottle, was developed to provide good short-period characteristics and rapid response to pilot inputs; and the attitude-hold feature minimized disturbances due to turbulence or variations in flaps and/or thrust. With this augmentation operative, the average pilot rating (PR) for the longitudinal handling qualities on the instrument approach was improved to satisfactory (PR < 3.5) for all four large transports simulated.

Laterally, a roll-rate-command/attitude-hold augmentation system was developed in an attempt to provide a rapid roll mode and quick uniform response to pilot inputs; the attitude-hold feature resulted in a desirable neutrally stable spiral mode while counteracting disturbances due to turbulence. Directionally, roll-rate and roll-attitude feedbacks were used to provide turn coordination and improved Dutch roll characteristics. Additionally, yaw-rate and sideslip feedbacks were used on the very large single-fuselage transport airplane to increase the Dutch roll undamped natural frequency and to counteract the large adverse sideslip exhibited by this configuration. With these systems operative, the average pilot ratings for the lateral-directional handling qualities on the instrument approach in calm air were improved to satisfactory for all transport airplanes except for the span-loader concept, in which the average pilot rating was 4.5 (acceptable, but unsatisfactory) primarily because of low roll response.

When simulated landing approaches were performed in 90° crosswinds, the pilots felt they could perform acceptable landings in crosswinds up to 30 knots on all transport airplanes except on the span-loader transport, for which crosswinds only up to 17 knots were acceptable. The landing-approach task, during these crosswind landings, was rated satisfactory for the triple-fuselage transport and acceptable for the very large single-fuselage and twin-fuselage transport airplanes.

During the simulator study described in NASA TP-2183, the roll-performance parameter $t_{\phi=30}$ (time required to bank 30°) was examined quite thoroughly; roll-response characteristics were "acceptable" when $t_{\phi=30}$ was less than 6 sec and were "satisfactory" when $t_{\phi=30}$ was less than 3.8 sec. The present simulator study confirms these findings. It is therefore suggested that this roll-performance criterion be validated by using in-flight simulation. In addition, it was determined that the maximum bank angle attained in the first second per unit wheel deflection (roll-response sensitivity) can be correlated for pilot ratings from previously published data for a range of effective wheel angles from 15° to 90°. For a pilot rating of 3 (satisfactory), the value of roll-response sensitivity was determined to be 0.1.

In general, it was concluded that the results of the present simulation study agree reasonably well with the handling qualities criteria used for comparison in this paper, except for some of the requirements described in NASA CR-159236 and for the roll-acceleration and roll-rate capability requirements. Data are presented that suggest that the lower boundaries of the roll-acceleration capability criterion be lowered for very large airplanes. It was also noted that the augmented very large transport configurations compared favorably with the reference transport.

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TABLE I. MASS AND DIMENSIONAL CHARACTERISTICS OF SIMULATED TRANSPORT AIRPLANES

(a) Very large single-fuselage transport

Weight:	
Takeoff, lbf	2 115 700
Landing, lbf	1 852 100
Reference wing area, ft^2	17 413
Wing span, ft	394.25
Wing leading-edge sweep, deg	37
Reference mean aerodynamic chord, ft	48.83
Center-of-gravity location, percent $\bar{c}$	35
Static margin, percent	−1.00
I_X, slug-ft^2	211 400 000
I_Y, slug-ft^2	319 200 000
I_Z, slug-ft^2	521 900 000
I_{XZ}, slug-ft^2	6 470 000
Maximum control-surface deflections:	
δ_f, deg (approach/landing)	26.1/50
δ_h, deg	7 to −5
δ_e, deg	±25
δ_a, deg	±40
δ_s, deg	0 to 60
δ_r, deg	±35
Maximum control-surface deflection rates:	
$\dot{\delta}_f$, deg/sec	±15
$\dot{\delta}_h$, deg/sec	±0.5
$\dot{\delta}_e$, deg/sec	±25
$\dot{\delta}_a$, deg/sec	±40
$\dot{\delta}_s$, deg/sec	±60
$\dot{\delta}_r$, deg/sec	±35
Horizontal tail:	
Gross horizontal-tail area, ft^2	1484
Mean aerodynamic chord, ft	17.92
Distance from center of gravity to horizontal tail $0.25\bar{c}$, ft	219.20
Vertical tail:	
Exposed vertical-tail area, ft^2	1710
Mean aerodynamic chord, ft	38.16
Distance from center of gravity to vertical tail $0.25\bar{c}$, ft	186.03
Engines:	
Lateral distance from center of gravity to engine centerline:	
Outboard, ft	128.3
Mid, ft	96.0
Inboard, ft	64.1
Vertical distance from center of gravity to engine centerline:	
Outboard, ft	10.7
Mid, ft	9.8
Inboard, ft	8.8

TABLE I. Continued

(b) Twin-fuselage transport

Weight:	
Takeoff, lbf	1 980 100
Landing, lbf	1 737 700
Reference wing area, ft^2	15 689
Wing span, ft	410.50
Wing leading-edge sweep, deg	27
Reference mean aerodynamic chord, ft	41.39
Center-of-gravity location, percent $\bar{c}$	34
Static margin, percent	1.00
I_X, slug-ft^2	370 900 000
I_Y, slug-ft^2	143 200 000
I_Z, slug-ft^2	486 100 000
I_{XZ}, slug-ft^2	3 880 000
Maximum control-surface deflections:	
δ_f, deg (approach/landing)	21.4/50
δ_h, deg	11 to 0
δ_e, deg	±25
δ_a, deg	±40
δ_s, deg	0 to 60
δ_r, deg	±35
Maximum control-surface deflection rates:	
$\dot{\delta}_f$, deg/sec	±15
$\dot{\delta}_h$, deg/sec	±0.5
$\dot{\delta}_e$, deg/sec	±25
$\dot{\delta}_a$, deg/sec	±40
$\dot{\delta}_s$, deg/sec	±60
$\dot{\delta}_r$, deg/sec	±35
Horizontal tail:	
Gross horizontal-tail area, ft^2	2085
Mean aerodynamic chord, ft	15.90
Distance from center of gravity to horizontal tail 0.25$\bar{c}$, ft	157.55
Vertical tail:	
Exposed vertical-tail area, ft^2	1436
Mean aerodynamic chord, ft	27.56
Distance from center of gravity to vertical tail 0.25$\bar{c}$, ft	136.13
Engines:	
Lateral distance from center of gravity to engine centerline:	
Outboard, ft	145.7
Mid, ft	106.8
Inboard, ft	15.9
Vertical distance from center of gravity to engine centerline:	
Outboard, ft	9.4
Mid, ft	7.6
Inboard, ft	7.0

TABLE I. Continued

(c) Triple-fuselage transport

Weight:	
Takeoff, lbf	2 013 900
Landing, lbf	1 753 600
Reference wing area, ft^2	14 555
Wing span, ft	427.27
Wing leading-edge sweep, deg	27
Reference mean aerodynamic chord, ft	36.89
Center-of-gravity location, percent $\bar{c}$	31
Static margin, percent	5.00
I_X, slug-ft^2	358 000 000
I_Y, slug-ft^2	78 900 000
I_Z, slug-ft^2	431 000 000
I_{XZ}, slug-ft^2	4 270 000
Maximum control-surface deflections:	
δ_f, deg (approach/landing)	36.9/50
δ_h, deg	7 to −8
δ_e, deg	±25
δ_a, deg	±40
δ_s, deg	0 to 60
δ_r, deg	±35
Maximum control-surface deflection rates:	
$\dot{\delta}_f$, deg/sec	±15
$\dot{\delta}_h$, deg/sec	±0.5
$\dot{\delta}_e$, deg/sec	±25
$\dot{\delta}_a$, deg/sec	±40
$\dot{\delta}_s$, deg/sec	±60
$\dot{\delta}_r$, deg/sec	±35
Horizontal tail:	
Gross horizontal-tail area, ft^2	3173
Mean aerodynamic chord, ft	19.43
Distance from center of gravity to horizontal tail 0.25$\bar{c}$, ft	133.30
Vertical tail:	
Exposed vertical-tail area, ft^2	2928
Mean aerodynamic chord, ft	35.01
Distance from center of gravity to vertical tail 0.25$\bar{c}$, ft	106.77
Engines:	
Lateral distance from center of gravity to engine centerline:	
Outboard, ft	156.0
Mid, ft	130.3
Inboard, ft	104.7
Vertical distance from center of gravity to engine centerline:	
Outboard, ft	9.4
Mid, ft	8.8
Inboard, ft	8.2

TABLE I. Continued

(d) Span-loader transport

Weight:	
Takeoff, lbf	1 543 300
Landing, lbf	1 339 000
Reference wing area, ft^2	18 559
Wing span, ft	331.0
Wing leading-edge sweep, deg	40
Reference mean aerodynamic chord, ft	56.25
Center-of-gravity location, percent $\bar{c}$	15
Static margin, percent	6.36
I_X, slug-ft^2	284 900 000
I_Y, slug-ft^2	122 600 000
I_Z, slug-ft^2	403 700 000
I_{XZ}, slug-ft^2	1 580 000
Maximum control-surface deflections:	
δ_f, deg (approach/landing)	30/40
δ_h, deg	20 to −5
δ_e, deg	±25
δ_a, deg	±40
δ_s, deg	0 to 60
δ_r, deg	±35
Maximum control-surface deflection rates:	
$\dot{\delta}_f$, deg/sec	±15
$\dot{\delta}_h$, deg/sec	±0.5
$\dot{\delta}_e$, deg/sec	±25
$\dot{\delta}_a$, deg/sec	±40
$\dot{\delta}_s$, deg/sec	±60
$\dot{\delta}_r$, deg/sec	±35
Horizontal tail:	
Gross horizontal-tail area, ft^2	3208
Mean aerodynamic chord, ft	26.75
Distance from center of gravity to horizontal tail 0.25$\bar{c}$, ft	−139.48
Vertical tail:	
Exposed vertical-tail area, ft^2	1779
Mean aerodynamic chord, ft	33.50
Distance from center of gravity to vertical tail 0.25$\bar{c}$, ft	73.87
Engines:	
Lateral distance from center of gravity to engine centerline:	
Outboard, ft	123.8
Mid, ft	82.9
Inboard, ft	41.3
Vertical distance from center of gravity to engine centerline:	
Outboard, ft	15.0
Mid, ft	15.0
Inboard, ft	15.0

TABLE I. Concluded

(e) Reference transport

Weight:	
Takeoff, lbf	769 000
Landing, lbf	579 000
Reference wing area, ft^2	6200
Wing span, ft	219.20
Wing leading-edge sweep, deg	28
Reference mean aerodynamic chord, ft	30.93
Center-of-gravity location, percent $\bar{c}$	35
Static margin, percent	10.77
I_X, slug-ft^2	34 900 000
I_Y, slug-ft^2	40 400 000
I_Z, slug-ft^2	60 100 000
I_{XZ}, slug-ft^2	60 600
Maximum control-surface deflections:	
δ_f, deg (approach/landing)	25/40
δ_h, deg	2 to −16.5
δ_e, deg	15 to −25
δ_a, deg	±40
δ_s, deg	0 to 60
δ_r, deg	±35
Maximum control-surface deflection rates:	
$\dot{\delta}_f$, deg/sec	±15
$\dot{\delta}_h$, deg/sec	±0.5
$\dot{\delta}_e$, deg/sec	±25
$\dot{\delta}_a$, deg/sec	±40
$\dot{\delta}_s$, deg/sec	±60
$\dot{\delta}_r$, deg/sec	±35
Horizontal tail:	
Gross horizontal-tail area, ft^2	965.82
Mean aerodynamic chord, ft	15.29
Distance from center of gravity to horizontal tail $0.25\bar{c}$, ft	125.87
Vertical tail:	
Exposed vertical-tail area, ft^2	961.07
Mean aerodynamic chord, ft	27.95
Distance from center of gravity to vertical tail $0.25\bar{c}$, ft	110.15
Engines:	
Lateral distance from center of gravity to engine centerline:	
Outboard, ft	61.9
Inboard, ft	39.8
Vertical distance from center of gravity to engine centerline:	
Outboard, ft	5.4
Inboard, ft	3.4

TABLE II.- PILOT RATING SYSTEM

CONTROLLABLE Capable of being controlled or managed in context of mission, with available pilot attention.	ACCEPTABLE May have deficiencies which warrant improvement, but adequate for mission. Pilot compensation, if required to achieve acceptable performance, is feasible.	SATISFACTORY Meets all requirements and expectations; good enough without improvement. Clearly adequate for mission.	Excellent, highly desirable.	1
			Good, pleasant, well behaved.	2
			Fair. Some mildly unpleasant characteristics. Good enough for mission without improvement.	3
		UNSATISFACTORY Reluctantly acceptable. Deficiencies which warrant improvement. Performance adequate for mission with feasible pilot compensation.	Some minor but annoying deficiencies. Improvement is requested. Effect on performance is easily compensated for by pilot.	4
			Moderately objectionable deficiencies. Improvement is needed. Reasonable performance requires considerable pilot compensation.	5
			Very objectionable deficiencies. Major improvements are needed. Requires best available pilot compensation to achieve acceptable performance.	6
	UNACCEPTABLE Deficiencies which require improvement. Inadequate performance for mission even with maximum feasible pilot compensation.		Major deficiencies which require improvement for acceptance. Controllable. Performance inadequate for mission, or pilot compensation required for minimum acceptable performance in mission is too high.	7
			Controllable with difficulty. Requires substantial pilot skill and attention to retain control and continue mission.	8
			Marginally controllable in mission. Requires maximum available pilot skill and attention to retain control.	9
UNCONTROLLABLE Control will be lost during some portion of mission.			Uncontrollable in mission.	10

TABLE III. TURBULENCE-EFFECT RATING SCALE

Increase of pilot effort with turbulence	Deterioration of task performance with turbulence	Rating
No significant increase	No significant deterioration	A
More effort required	No significant deterioration	B
	Minor	C
	Moderate	D
Best efforts required	Moderate	E
	Major (but evaluation tasks can still be accomplished)	F
	Large (some tasks cannot be performed)	G
Unable to perform tasks		H

TABLE IV. DYNAMIC STABILITY CHARACTERISTICS OF SIMULATED LARGE SUBSONIC TRANSPORT AIRPLANES

(a) Very large single-fuselage transport

Parameter	$V_{app}/\delta_f = 147.4/26.1$		$V_{\ell}/\delta_f = 142.5/50$		Satisfactory criterion	Acceptable criterion
	Unaugmented	SCAS (a)	Unaugmented	SCAS (a)		
Short-period mode						
$\tau_{p,\mathrm{eff}}$, sec	2.37	0.76	2.41	0.79		
ω_{sp}, rad/sec		1.137		1.094	Figs. 7(a), 12	Figs. 7(a), 12
P_{sp}, sec		10.16		9.93		
ζ_{sp}		0.839		0.816	0.35 to 1.30	0.25 to 2.00
L_α/ω_{sp}		0.385		0.387	Fig. 7(b)	Fig. 7(b)
n/α, g units/rad		3.49		3.26	Fig. 7(a)	Fig. 7(a)
Longitudinal (aperiodic) mode						
t_2, sec	47.70		54.41			> 6
Long-period mode						
ω_{ph}, rad/sec	0.168	0.217	0.183	0.243		
P_{ph}, sec	104.92		68.34			
ζ_{ph}	0.934	1.279	0.864	1.133	≥ 0.04	≥ 0
Roll-spiral mode						
τ_R or $\tau_{R,\mathrm{eff}}$, sec	1.10	[b]0.50	1.12	[b]0.42	≤ 1.4	≤ 3.0
t_{s2}, sec	[c]−76.93	214.40	[c]−76.01	372.66	≥ 12	≥ 8
ω_{ra}, rad/sec		6.314		7.295		
ζ_{ra}		0.781		0.673		
$\zeta_{ra}\omega_{ra}$, rad/sec		4.929		4.909	≥ 0.5	≥ 0.3
P_{ra}, sec		1.59		1.16		
Dutch roll mode						
ω_d, rad/sec	0.390	0.620	0.380	0.614	≥ 0.4	≥ 0.4
ζ_d	0.100	0.177	0.087	0.175	≥ 0.08	≥ 0.02
$\zeta_d\omega_d$, rad/sec	0.039	0.110	0.033	0.108	≥ 0.10	≥ 0.05
P_d, sec	16.20	10.30	16.62	10.40		
ϕ/β	0.952	∞	0.911	∞		
Roll control parameters						
ω_ϕ/ω_d	0.829	1.001	0.873	0.998	0.80 to 1.15	0.65 to 1.35
ζ_ϕ/ζ_d	2.047	1.049	2.355	1.038		

[a]Autothrottle on.
[b]Value of $\tau_{R,\mathrm{eff}}$.
[c]Minus sign signifies time to half-amplitude.

TABLE IV. Continued

(b) Twin-fuselage transport

Parameter	$V_{app}/\delta_f = 141.7/21.4$		$V_\ell/\delta_f = 130.5/50$		Satisfactory criterion	Acceptable criterion
	Unaugmented	SCAS (a)	Unaugmented	SCAS (a)		
Short-period mode						
$\tau_{p,\mathrm{eff}}$, sec	2.14	0.56	2.43	0.65		
ω_{sp}, rad/sec	0.384	1.696	0.156	1.497	Figs. 7(a), 12	Figs. 7(a), 12
P_{sp}, sec		24.71		9.66		
ζ_{sp}	1.172	0.989	2.150	0.901	0.35 to 1.30	0.25 to 2.00
$L_\alpha/\omega_{\mathrm{sp}}$	1.088	0.247	2.465	0.257	Fig. 7(b)	Fig. 7(b)
n/α, g units/rad . .	3.20	3.20	2.71	2.71	Fig. 7(a)	Fig. 7(a)
Longitudinal (aperiodic) mode						
t_2, sec						> 6
Long-period mode						
ω_{ph}, rad/sec	0.061	0.217	0.148	0.242		
P_{ph}, sec	193.74		120.83			
ζ_{ph}	0.848	1.148	0.937	1.016	≥ 0.04	≥ 0
Roll-spiral mode						
τ_R or $\tau_{R,\mathrm{eff}}$, sec . .	1.48	[b]0.74	1.58	[b]0.69	≤ 1.4	≤ 3.0
t_{s2}, sec	100.82		100.63		≥ 12	≥ 8
ω_{rs}, rad/sec		3.107		3.665		
ζ_{rs}		0.674		0.696		
$\zeta_{\mathrm{rs}}\omega_{\mathrm{rs}}$, rad/sec . . .		2.093		2.550	≥ 0.5	≥ 0.3
P_{rs}, sec		2.74		2.39		
Dutch roll mode						
ω_d, rad/sec	0.332	0.266	0.311	0.248	≥ 0.4	≥ 0.4
ζ_d	0.104	0.255	0.093	0.253	≥ 0.08	≥ 0.02
$\zeta_d\omega_d$, rad/sec . . .	0.035	0.068	0.029	0.063	≥ 0.10	≥ 0.05
P_d, sec	19.04	24.47	20.30	26.23		
ϕ/β	0.781	0.042	0.707	0.023		
Roll control parameters						
ω_ϕ/ω_d	0.794	0.999	0.791	1.000	0.80 to 1.15	0.65 to 1.35
ζ_ϕ/ζ_d	1.968	1.006	2.251	0.998		

[a]Autothrottle on.
[b]Value of $\tau_{R,\mathrm{eff}}$.

TABLE IV. Continued

(c) Triple-fuselage transport

Parameter	$V_{app}/\delta_f = 146.5/36.9$ Unaugmented	$V_{app}/\delta_f = 146.5/36.9$ SCAS (a)	$V_{\ell}/\delta_f = 142.3/50$ Unaugmented	$V_{\ell}/\delta_f = 142.3/50$ SCAS (a)	Satisfactory criterion	Acceptable criterion
Short-period mode						
$\tau_{p,\mathrm{eff}}$, sec	0.92	0.38	0.94	0.40		
ω_{sp}, rad/sec	0.670	2.793	0.648	2.668	Figs. 7(a), 12	Figs. 7(a), 12
P_{sp}, sec		3.17		3.25		
ζ_{sp}	1.109	0.705	1.112	0.688	0.35 to 1.30	0.25 to 2.00
L_α/ω_{sp}	0.589	0.141	0.608	0.148	Fig. 7(b)	Fig. 7(b)
n/α, g units/rad	3.15	3.15	3.07	3.07	Fig. 7(a)	Fig. 7(a)
Longitudinal (aperiodic) mode						
t_2, sec						> 6
Long-period mode						
ω_{ph}, rad/sec	0.096	0.225	0.099	0.228		
P_{ph}, sec	69.55		67.54			
ζ_{ph}	0.349	1.065	0.352	1.033	≥ 0.04	≥ 0
Roll-spiral mode						
τ_R or $\tau_{R,\mathrm{eff}}$, sec	1.36	[b]0.71	1.40	[b]0.57	≤ 1.4	≤ 3.0
t_{s2}, sec	53.04		54.59		≥ 12	≥ 8
ω_{rs}, rad/sec		2.911		2.442		
ζ_{rs}		0.529		0.506		
$\zeta_{rs}\omega_{rs}$, rad/sec		1.540		1.236	≥ 0.5	≥ 0.3
P_{rs}, sec		2.54		2.98		
Dutch roll mode						
ω_d, rad/sec	0.396	0.327	0.383	0.336	≥ 0.4	≥ 0.4
ζ_d	0.130	0.241	0.128	0.237	≥ 0.08	≥ 0.02
$\zeta_d\omega_d$, rad/sec	0.052	0.079	0.049	0.080	≥ 0.10	≥ 0.05
P_d, sec	15.99	19.82	16.55	19.24		
ϕ/β	0.653	0.055	0.635	0.044		
Roll control parameters						
ω_ϕ/ω_d	0.843	0.999	0.848	0.999	0.80 to 1.15	0.65 to 1.35
ζ_ϕ/ζ_d	1.584	0.998	1.660	0.999		

[a]Autothrottle on.
[b]Value of $\tau_{R,\mathrm{eff}}$.

TABLE IV. Continued

(d) Span-loader transport

Parameter	$V_{app}/\delta_f = 123/30$ Unaugmented	$V_{app}/\delta_f = 123/30$ SCAS (a)	$V_\ell/\delta_f = 120/40$ Unaugmented	$V_\ell/\delta_f = 120/40$ SCAS (a)	Satisfactory criterion	Acceptable criterion
Short-period mode						
$\tau_{p,\mathrm{eff}}$, sec	0.83	0.99	0.87	1.01		
ω_{sp}, rad/sec	0.715	1.373	0.702	1.575	Figs. 7(a), 12	Figs. 7(a), 12
P_{sp}, sec				11.76		
ζ_{sp}	1.264	1.013	1.247	0.941	0.35 to 1.30	0.25 to 2.00
L_α/ω_{sp}	0.601	0.313	0.597	0.266	Fig. 7(b)	Fig. 7(b)
n/α, g units/rad	2.86	2.86	2.72	2.72	Fig. 7(a)	Fig. 7(a)
Longitudinal (aperiodic) mode						
t_2, sec						> 6
Long-period mode						
ω_{ph}, rad/sec	0.099	0.299	0.080	0.285		
P_{ph}, sec	75.05	100.20		32.29		
ζ_{ph}	0.528	0.977	1.010	0.731	≥ 0.04	≥ 0
Roll-spiral mode						
τ_R or $\tau_{R,\mathrm{eff}}$, sec	2.31	[b]0.90	2.33	[b]0.85	≤ 1.4	≤ 3.0
t_{s2}, sec	35.46		35.49		≥ 12	≥ 8
ω_{rs}, rad/sec		1.613		1.677		
ζ_{rs}		0.545		0.551		
$\zeta_{rs}\omega_{rs}$, rad/sec		0.879		0.923	≥ 0.5	≥ 0.3
P_{rs}, sec		4.65		4.49		
Dutch roll mode						
ω_d, rad/sec	0.379	0.316	0.371	0.319	≥ 0.4	≥ 0.4
ζ_d	0.015	0.219	0.004	0.213	≥ 0.08	≥ 0.02
$\zeta_d\omega_d$, rad/sec	0.006	0.069	0.002	0.068	≥ 0.10	≥ 0.05
P_d, sec	16.57	20.35	16.93	20.15		
ϕ/β	1.117	0.133	1.086	0.111		
Roll control parameters						
ω_ϕ/ω_d	0.830	0.991	0.855	0.997	0.80 to 1.15	0.65 to 1.35
ζ_ϕ/ζ_d	13.09	1.005	45.81	1.000		

[a]Autothrottle on.

[b]Value of $\tau_{R,\mathrm{eff}}$.

TABLE IV. Concluded

(e) Reference transport

Parameter	$V_{app}/\delta_f = 135/25$ Unaugmented	$V_{app}/\delta_f = 135/25$ SAS (a)	$V_\ell/\delta_f = 128/40$ Unaugmented	$V_\ell/\delta_f = 128/40$ SAS (a)	Satisfactory criterion	Acceptable criterion
Short-period mode						
ω_{sp}, rad/sec	0.675	0.754	0.645	0.706	Figs. 7(a), 12	Figs. 7(a), 12
P_{sp}, sec	18.80	23.79	19.73	25.99		
ς_{sp}	0.869	0.937	0.870	0.940	0.35 to 1.30	0.25 to 2.00
L_α/ω_{sp}	0.829	0.742	0.823	0.752	Fig. 7(b)	Fig. 7(b)
n/α, g units/rad . .	3.96	3.96	3.56	3.56	Fig. 7(a)	Fig. 7(a)
Longitudinal (aperiodic) mode						
t_2, sec		[b]-35.69		[b]-35.82		> 6
Long-period mode						
ω_{ph}, rad/sec	0.122		0.129			
P_{ph}, sec	51.39		48.72			
ς_{ph}	0.045		0.072		≥ 0.04	≥ 0
Roll-spiral mode						
τ_R, sec	1.75	2.31	1.79	3.35	≤ 1.4	≤ 3.0
t_{s2}, sec	10.75	[b]-28.20	10.37	[b]-3.41	≥ 12	≥ 8
ω_{rs}, rad/sec						
ς_{rs}						
$\varsigma_{rs}\omega_{rs}$, rad/sec . . .					≥ 0.5	≥ 0.3
P_{rs}, sec						
Dutch roll mode						
ω_d, rad/sec	0.579	0.432	0.553	0.395	≥ 0.4	≥ 0.4
ς_d	0.135	0.544	0.125	0.445	≥ 0.08	≥ 0.02
$\varsigma_d\omega_d$, rad/sec . . .	0.078	0.235	0.069	0.176	≥ 0.10	≥ 0.05
P_d, sec	10.95	17.33	11.44	17.77		
ϕ/β	1.053	0.850	1.187	0.861		
Roll control parameters						
ω_ϕ/ω_d	0.824	1.148	0.857	1.243	0.80 to 1.15	0.65 to 1.35
$\varsigma_\phi/\varsigma_d$	1.951	0.818	2.332	1.022		

[a]Autothrottle on.
[b]Minus sign signifies time to half-amplitude.

TABLE V. CONTROL-RESPONSE CHARACTERISTICS OF SIMULATED LARGE SUBSONIC-CRUISE TRANSPORT AIRPLANES

(a) Very large single-fuselage transport

Parameter	$V_{app}/\delta_f = 147.4/26.1$		$V_{app}/\delta_f = 142.5/50$		Satisfactory criterion	Acceptable criterion
	Unaugmented	SCAS (a)	Unaugmented	SCAS (a)		
Longitudinal						
$\ddot{\theta}_{max}$, rad/sec^2	[b]−0.039	[b]−0.039	[b]−0.037	[b]−0.037	[b]−0.055	[b]−0.035
$\dot{\theta}/\dot{\theta}_{ss}$					Fig. 13(a)[c]	
$\Delta a_n/\ddot{\theta}$, g units/(deg/sec^2)						Fig. 6[c]
t_1, sec	0.06	0.15	0.05	0.15	≤0.200	≤0.283
Δt, sec	2.54	0.94	2.57	0.99	[c]0.037 to 0.828	[c]0.013 to 2.671
$\Delta\dot{\theta}_2/\Delta\dot{\theta}_1$	0	0	0	0	≤0.30	≤0.60
Lateral						
$\ddot{\phi}_{max}$, rad/sec^2	0.121	0.119	0.166	0.162	Fig. 21	Fig. 21
$\dot{\phi}_{max}$, deg/sec	10.70	12.39	15.34	12.86		Fig. 24
p_2/p_1	0.414	1.000	0.479	1.000	≥0.60	≥0.25
ϕ_{osc}/ϕ_{av}					Fig. 25	Fig. 25
$t_{\phi=30}$, sec	4.09	3.99	3.32	3.45	≤2.5	≤4.0
t_1, sec	0.03	0.03	0.05	0.05	≤0.283	≤0.400
Δt, sec	1.28	0.58	1.32	0.40		

[a]Autothrottle on.
[b]Minimum demonstrated speed = $1.06V_s$.
[c]Landing configuration.

TABLE V. Continued

(b) Twin-fuselage transport

Parameter	$V_{app}/\delta_f = 141.7/26.1$		$V_{app}/\delta_f = 130.5/50$		Satisfactory criterion	Acceptable criterion
	Unaugmented	SCAS (a)	Unaugmented	SCAS (a)		
Longitudinal						
$\ddot{\theta}_{max}$, rad/sec^2	[b]-0.054	[b]-0.054	[b]-0.046	[b]-0.046	[b]-0.055	[b]-0.035
$\dot{\theta}/\dot{\theta}_{ss}$					Fig. 13(b)[c]	
$\Delta a_n/\ddot{\theta}$, g units/(deg/sec^2)						Fig. 6[c]
t_1, sec	0.06	0.15	0.08	0.16	$\leq$0.200	$\leq$0.283
Δt, sec	2.44	0.68	2.45	0.75	[c]0.040 to 0.882	[c]0.014 to 2.843
$\Delta\dot{\theta}_2/\Delta\dot{\theta}_1$	0	0	0	0	$\leq$0.30	$\leq$0.60
Lateral						
$\ddot{\phi}_{max}$, rad/sec^2	0.058	0.057	0.071	0.070	Fig. 21	Fig. 21
$\dot{\phi}_{max}$, deg/sec	6.34	8.03	8.20	9.55		Fig. 24
p_2/p_1	0.382	1.000	0.462	1.000	$\geq$0.60	$\geq$0.25
ϕ_{osc}/ϕ_{av}	0.303	0.003	0.333	0.003	Fig. 25	Fig. 25
$t_{\phi=30}$, sec	6.31	5.86	5.30	5.11	$\leq$2.5	$\leq$4.0
t_1, sec	0.08	0.14	0.06	0.12	$\leq$0.283	$\leq$0.400
Δt, sec	1.63	0.55	1.70	0.53		

[a]Autothrottle on.
[b]Minimum demonstrated speed = $1.06V_s$.
[c]Landing configuration.

TABLE V. Continued

(c) Triple-fuselage transport

Parameter	$V_{app}/\delta_f = 146.5/36.9$		$V_{app}/\delta_f = 142.3/50$		Satisfactory criterion	Acceptable criterion
	Unaugmented	SCAS (a)	Unaugmented	SCAS (a)		
Longitudinal						
$\ddot{\theta}_{max}$, rad/sec^2	[b]-0.112	[b]-0.112	[b]-0.107	[b]-0.107	[b]-0.055	[b]-0.035
$\dot{\theta}/\dot{\theta}_{ss}$					Fig. 13(c)[c]	
$\Delta a_n/\ddot{\theta}$, g units/(deg/sec^2)						Fig. 6[c]
t_1, sec	0.03	0.06	0.03	0.07	≤ 0.200	≤ 0.283
Δt, sec	1.22	0.50	1.23	0.52	[c]0.036 to 0.809	[c]0.013 to 2.608
$\Delta\dot{\theta}_2/\Delta\dot{\theta}_1$	0	0.047	0	0.101	≤ 0.30	≤ 0.60
Lateral						
$\ddot{\phi}_{max}$, rad/sec^2	0.060	0.059	0.079	0.078	Fig. 21	Fig. 21
$\dot{\phi}_{max}$, deg/sec	6.19	7.50	8.50	9.71		Fig. 24
p_2/p_1	0.598	1.000	0.610	1.000	≥ 0.60	≥ 0.25
ϕ_{osc}/ϕ_{av}	0.151	0.001	0.144	0	Fig. 25	Fig. 25
$t_{\phi=30}$, sec	6.38	5.95	5.04	4.91	≤ 2.5	≤ 4.0
t_1, sec	0.01	0.13	0.05	0.11	≤ 0.283	≤ 0.400
Δt, sec	1.67	0.96	1.59	0.76		

[a]Autothrottle on.
[b]Minimum demonstrated speed = $1.06V_s$.
[c]Landing configuration.

TABLE V. Continued

(d) Span-loader transport

Parameter	$V_{app}/\delta_f = 123/30$ Unaugmented	$V_{app}/\delta_f = 123/30$ SCAS (a)	$V_{app}/\delta_f = 120/40$ Unaugmented	$V_{app}/\delta_f = 120/40$ SCAS (a)	Satisfactory criterion	Acceptable criterion
Longitudinal						
$\ddot{\theta}_{max}$, rad/sec^2	[b]-0.031	[b]-0.031	[b]-0.030	[b]-0.030	[b]-0.055	[b]-0.035
$\dot{\theta}/\dot{\theta}_{ss}$					Fig. 13(d)[c]	
$\Delta a_n/\ddot{\theta}$, g units/(deg/sec^2)						Fig. 6[c]
t_1, sec	0.03	0.27	0.03	0.32	≤ 0.200	≤ 0.283
Δt, sec	1.10	1.12	1.10	1.11	[c]0.043 to 0.959	[c]0.015 to 3.092
$\Delta\dot{\theta}_2/\Delta\dot{\theta}_1$	0	0	0	0	≤ 0.30	≤ 0.60
Lateral						
$\ddot{\phi}_{max}$, rad/sec^2	0.054	0.053	0.058	0.057	Fig. 21	Fig. 21
$\dot{\phi}_{max}$, deg/sec	8.47	10.84	9.77	11.97		Fig. 24
p_2/p_1	0.415	1.000	0.468	1.000	≥ 0.60	≥ 0.25
ϕ_{osc}/ϕ_{av}	0.233	0.023	0.226	0.021	Fig. 25	Fig. 25
$t_{\phi=30}$, sec	6.12	5.95	5.78	5.67	≤ 2.5	≤ 4.0
t_1, sec	0.12	0.43	0.13	0.43	≤ 0.283	≤ 0.400
Δt, sec	2.53	3.56	2.49	3.29		

[a]Autothrottle on.
[b]Minimum demonstrated speed = $1.06V_s$.
[c]Landing configuration.

TABLE V. Concluded

(e) Reference transport

Parameter	$V_{app}/\delta_f = 135/25$		$V_{app}/\delta_f = 128/40$		Satisfactory criterion	Acceptable criterion
	Unaugmented	SAS (a)	Unaugmented	SAS (a)		
Longitudinal						
$\ddot{\theta}_{max}$, rad/sec^2	[b]−0.051	[b]−0.051	[b]−0.046	[b]−0.046	[b]−0.055	[b]−0.035
$\theta/\dot{\theta}_{ss}$					Fig. 13(a)[c]	
$\Delta a_n/\ddot{\theta}$, g units/(deg/sec^2)						Fig. 6[c]
t_1, sec	0.05	0.03	0.05	0.03	≤0.200	≤0.283
Δt, sec	1.58	1.42	1.71	1.35	[c]0.041 to 0.901	[c]0.014 to 2.905
$\Delta\dot{\theta}_2/\Delta\dot{\theta}_1$	0	0.14	0	0.18	≤0.30	≤0.60
Lateral						
$\ddot{\phi}_{max}$, rad/sec^2	0.121	0.120	0.155	0.153	Fig. 21	Fig. 21
$\dot{\phi}_{max}$, deg/sec	15.56	17.25	20.86	22.52		Fig. 24
p_2/p_1	0.865	0.854	0.930	0.918	≥0.60	≥0.25
ϕ_{osc}/ϕ_{av}					Fig. 25	Fig. 25
$t_{\phi=30}$, sec	3.6	3.6	3.1	3.1	≤2.5	≤4.0
t_1, sec	0.15	0.15	0.16	0.16	≤0.283	≤0.400
Δt, sec		2.90		2.51		

[a]Autothrottle on.
[b]Minimum demonstrated speed = $1.06V_s$.
[c]Landing configuration.

TABLE VI. FLIGHT-CONTROL-SYSTEM GAINS

(a) Pitch axis

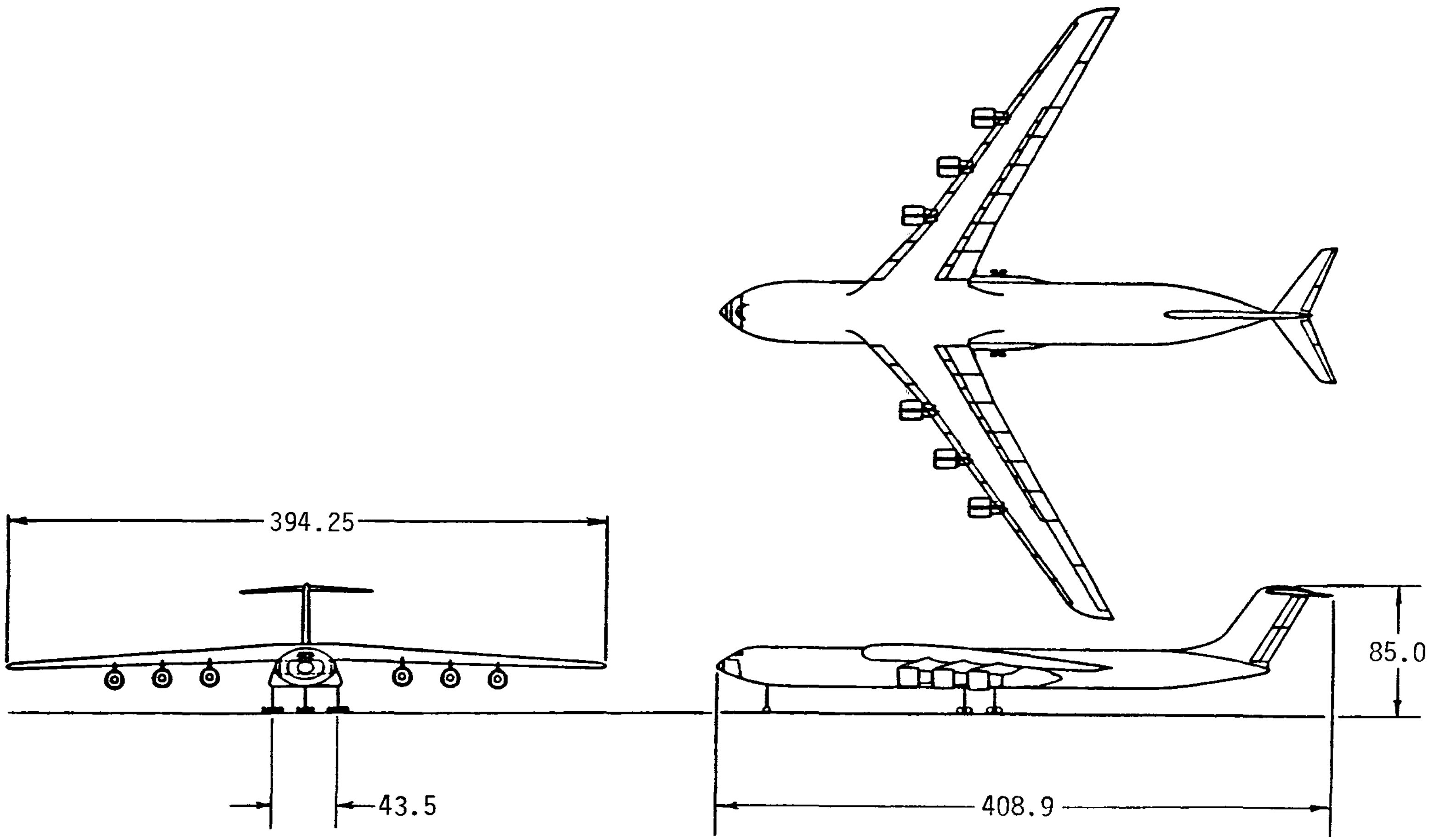
Airplane	$K_{q,c}$, $\frac{\text{deg/sec}}{\text{in.}}$	K_θ, deg/deg	$K_{\theta,H}$, $\frac{\text{deg/sec}}{\text{deg/sec}}$	K_q, $\frac{\text{deg}}{\text{deg/sec}}$	$K_{q,I}$, $\frac{\text{deg/sec}}{\text{deg/sec}}$
Single fuselage . .	1.5	1.0	0.95	7.0	6.0
Twin fuselage . .	1.5	1.0	1.01	9.0	8.0
Triple fuselage . .	1.5	1.0	1.01	1.0	1.2
Span loader . . .	2.5	1.0	0.95	6.0	8.0

(b) Roll axis

Airplane	$K_{p,c}$, $\frac{\text{deg/sec}}{\text{deg}}$	K_p, $\frac{\text{deg}}{\text{deg/sec}}$	$K_{p,I}$, deg/deg	$K_{\phi,\mathrm{TC}}$, sec^{-1}	$K_{\phi,2}$, deg/deg	K_{WL}, deg/deg	p_{RAH}, deg/sec	$\delta_{w,\mathrm{RAH}}$, deg	ϕ_{WL}, deg
Single fuselage . .	0.20	15.0	5.0	−50.0	10.0	1.0	4.0	0.3	2.0
Twin fuselage . .	0.35	25.0	2.0	−50.0	50.0	1.0	0.25	0.3	2.0
Triple fuselage . .	0.35	25.0	2.0	−50.0	35.0	1.0	0.25	0.3	2.0
Span loader . . .	0.35	15.0	4.0	−50.0	20.0	1.0	3.0	0.3	2.0

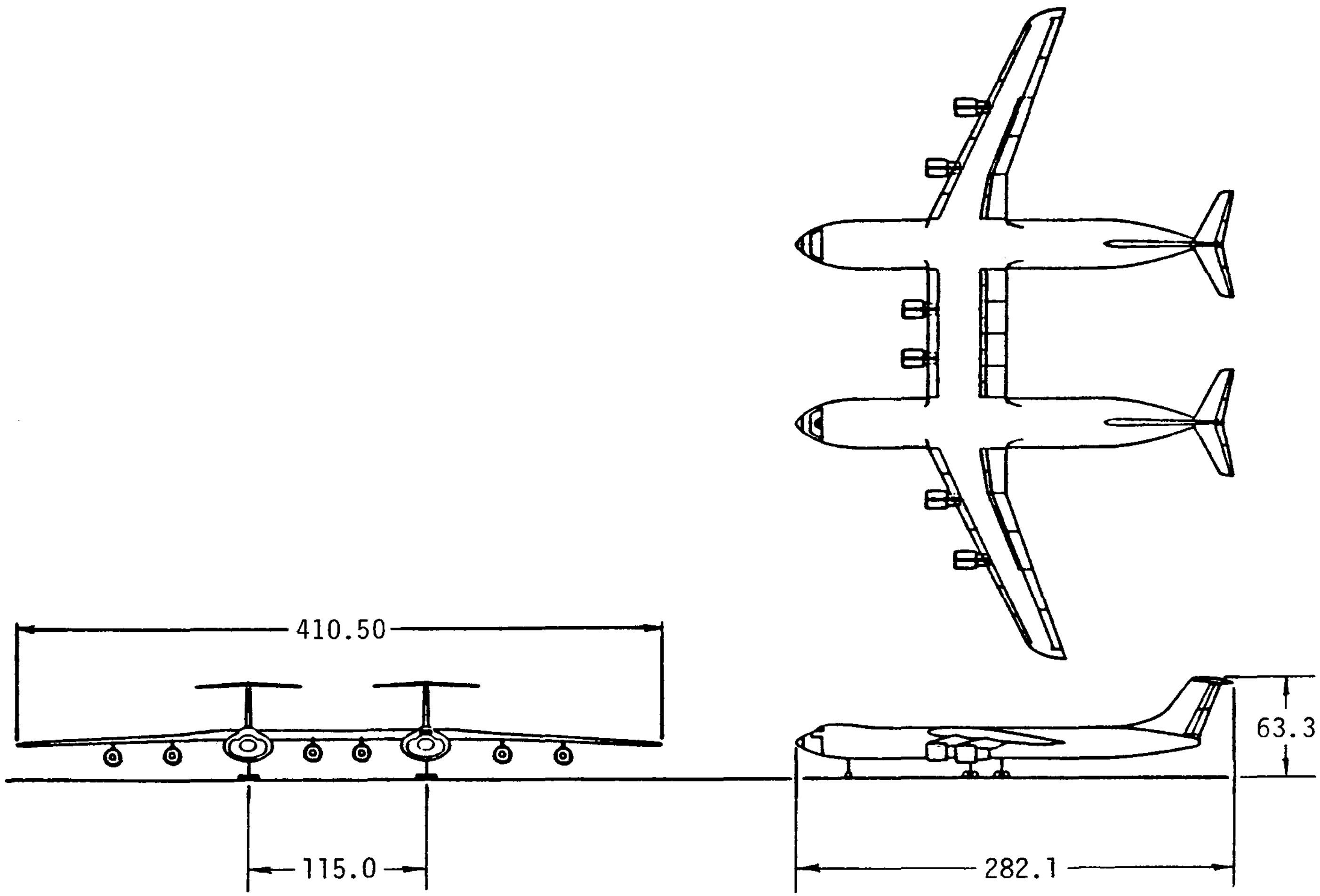
(c) Yaw axis

Airplane	$K_{\phi,R}$, deg/deg	$K_{p,Y}$, $\frac{\text{deg}}{\text{deg/sec}}$	K_r, $\frac{\text{deg}}{\text{deg/sec}}$	K_β, deg/deg
Single fuselage . .	−0.30	−4.0	1.0	−5.0
Twin fuselage . .	−0.35	−5.3	0	0
Triple fuselage . .	−0.35	−5.3	0	0
Span loader . . .	−0.20	−2.6	0	0



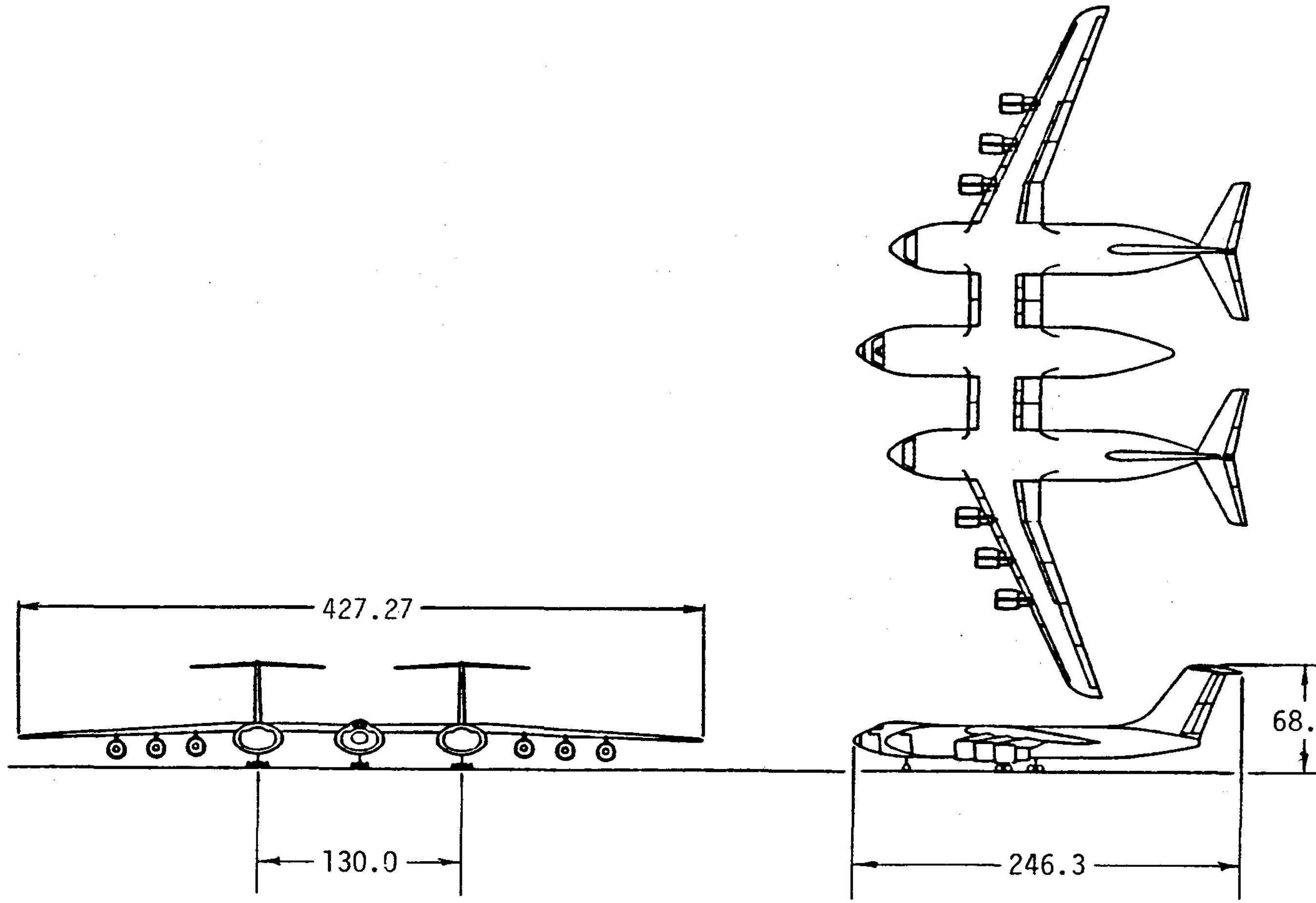
(a) Very large single-fuselage transport.

Figure 1. Three-view sketches of large transports simulated. All linear dimensions are given in feet.



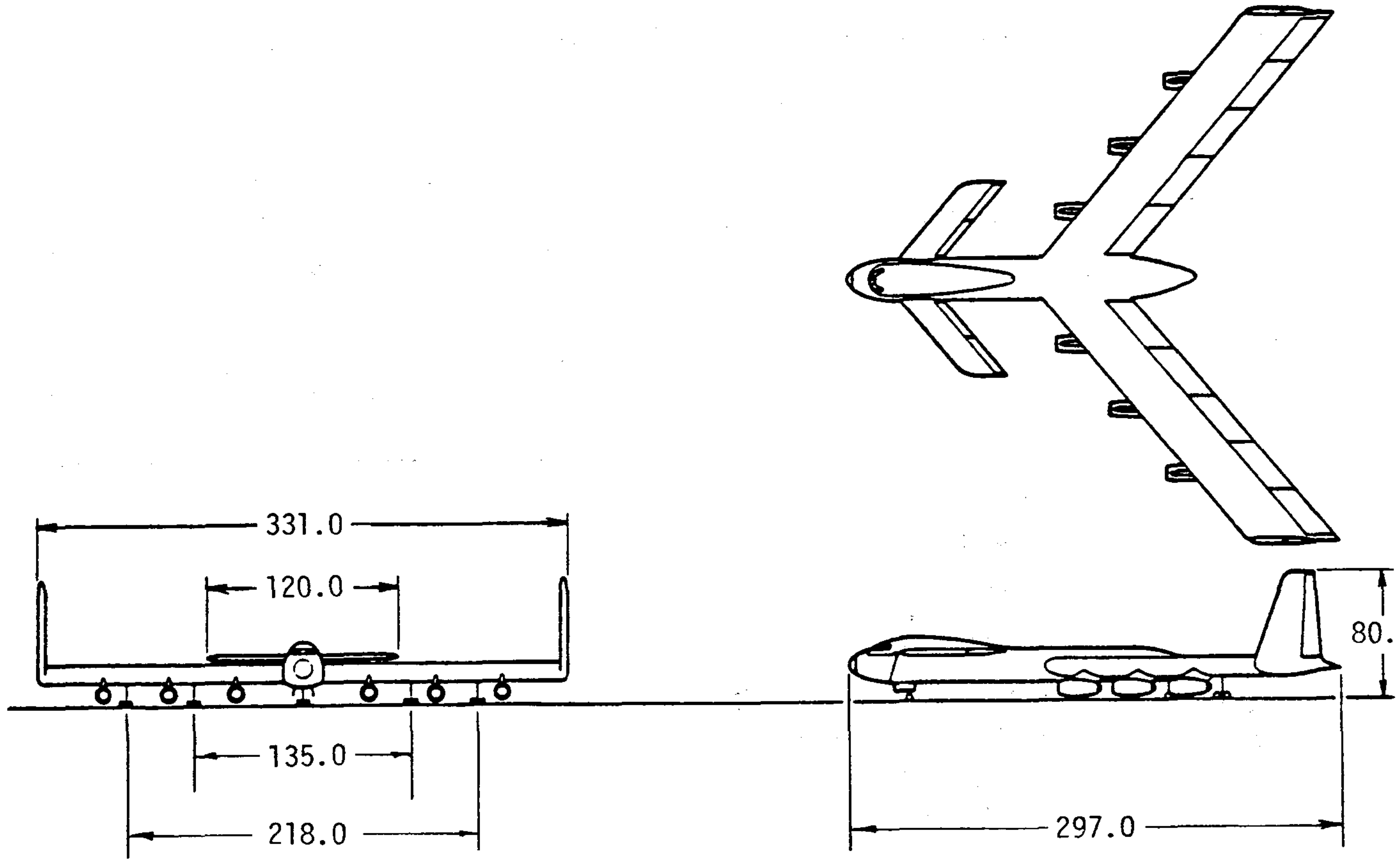
(b) Twin-fuselage transport.

Figure 1. Continued.



(c) Triple-fuselage transport.

Figure 1. Continued.



(d) Span-loader transport.

Figure 1. Concluded.

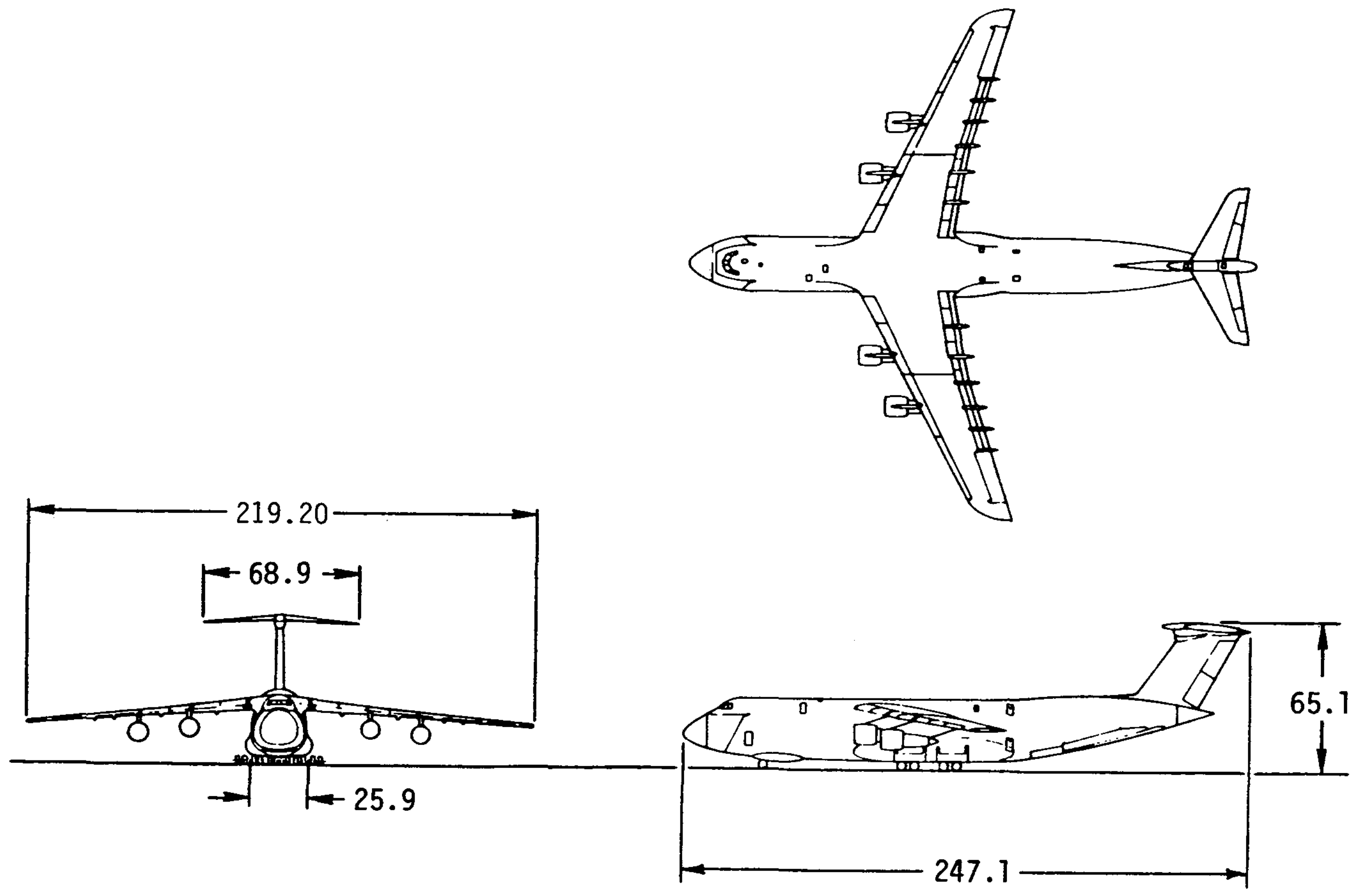


Figure 2. Three-view sketch of reference transport simulated. All linear dimensions are given in feet.

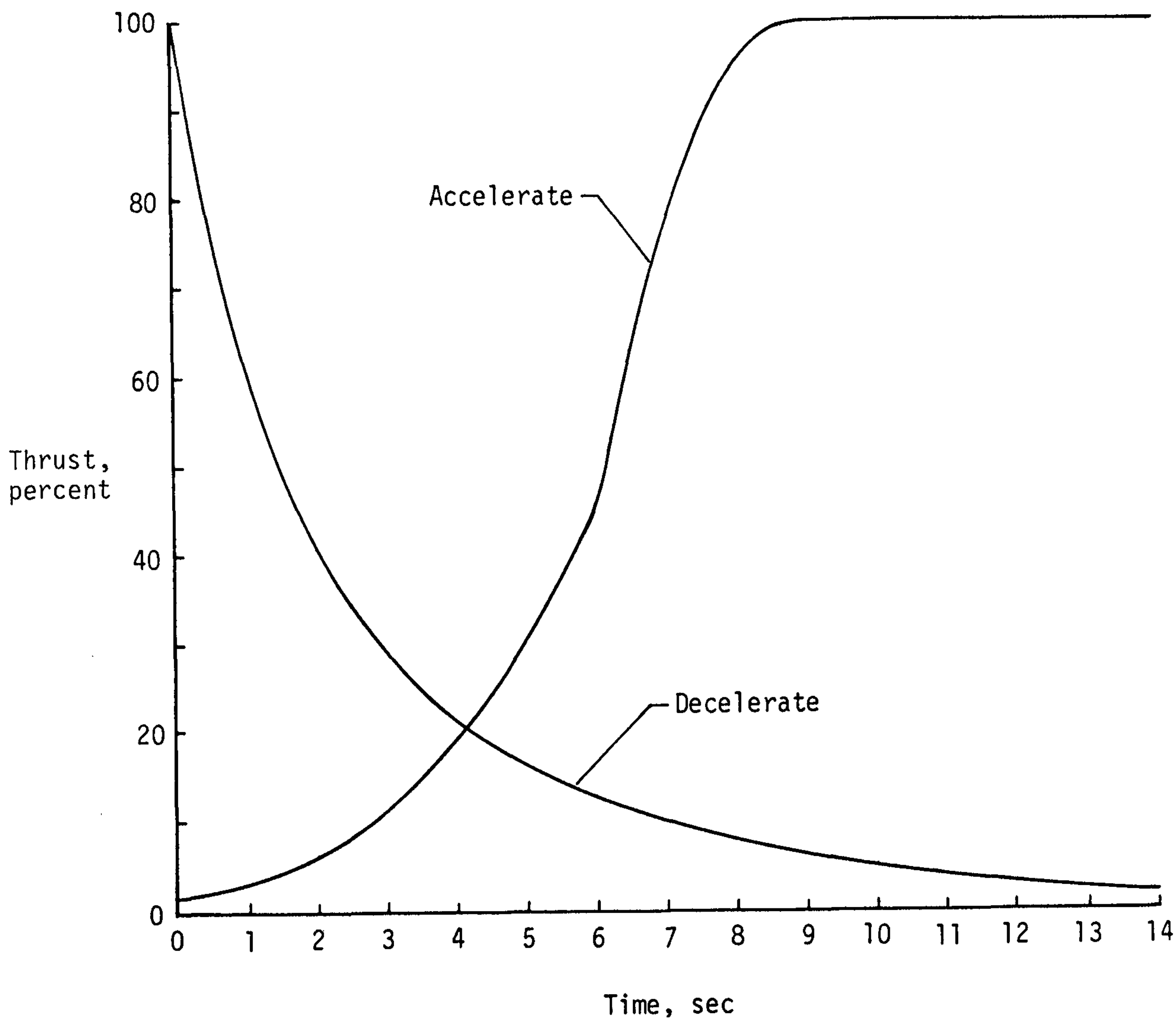
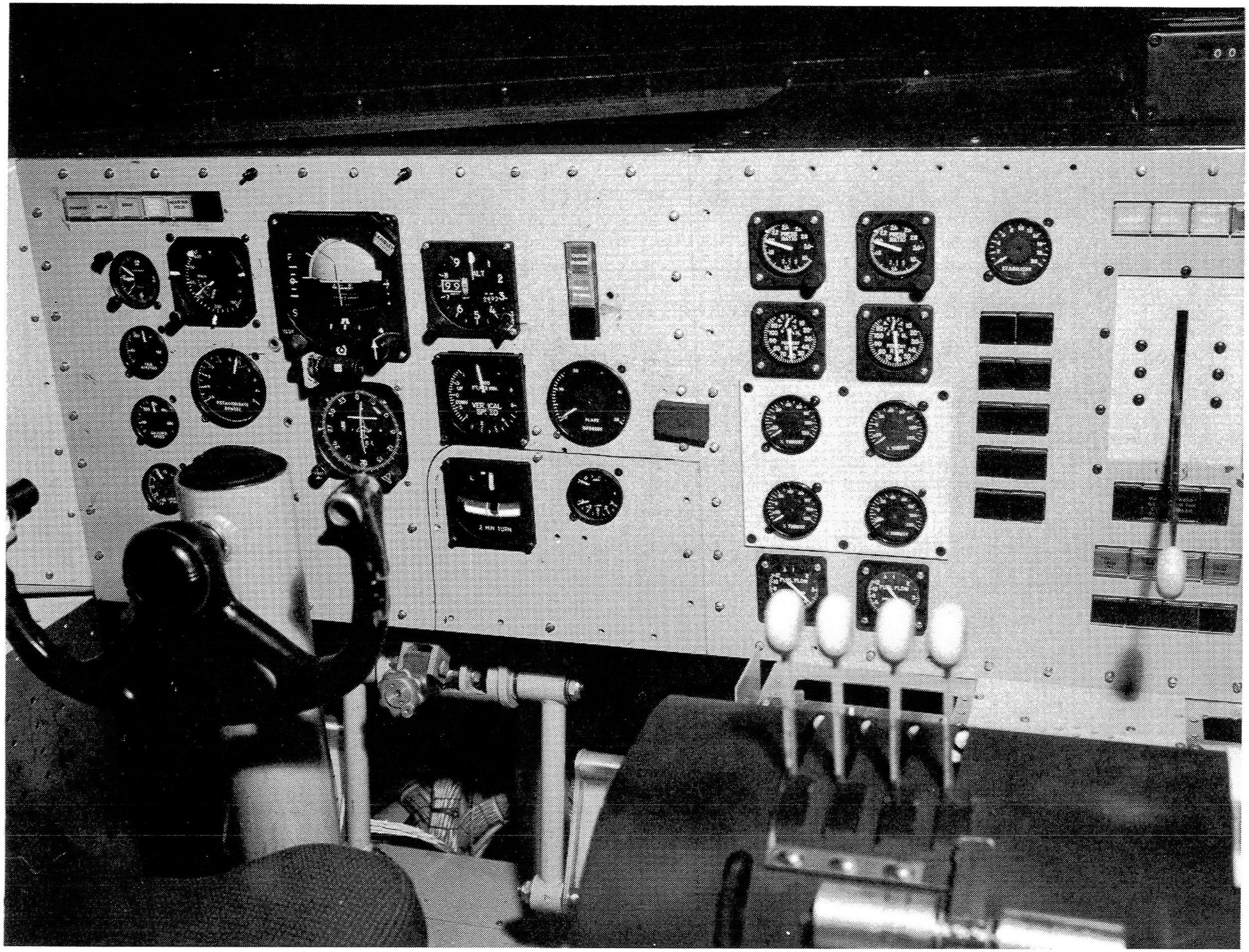


Figure 3. Example of engine-thrust response characteristics to a step "throttle" input used in simulation of all transport airplanes in present study.

L-75-7570

(a) Langley Visual/Motion Simulator.

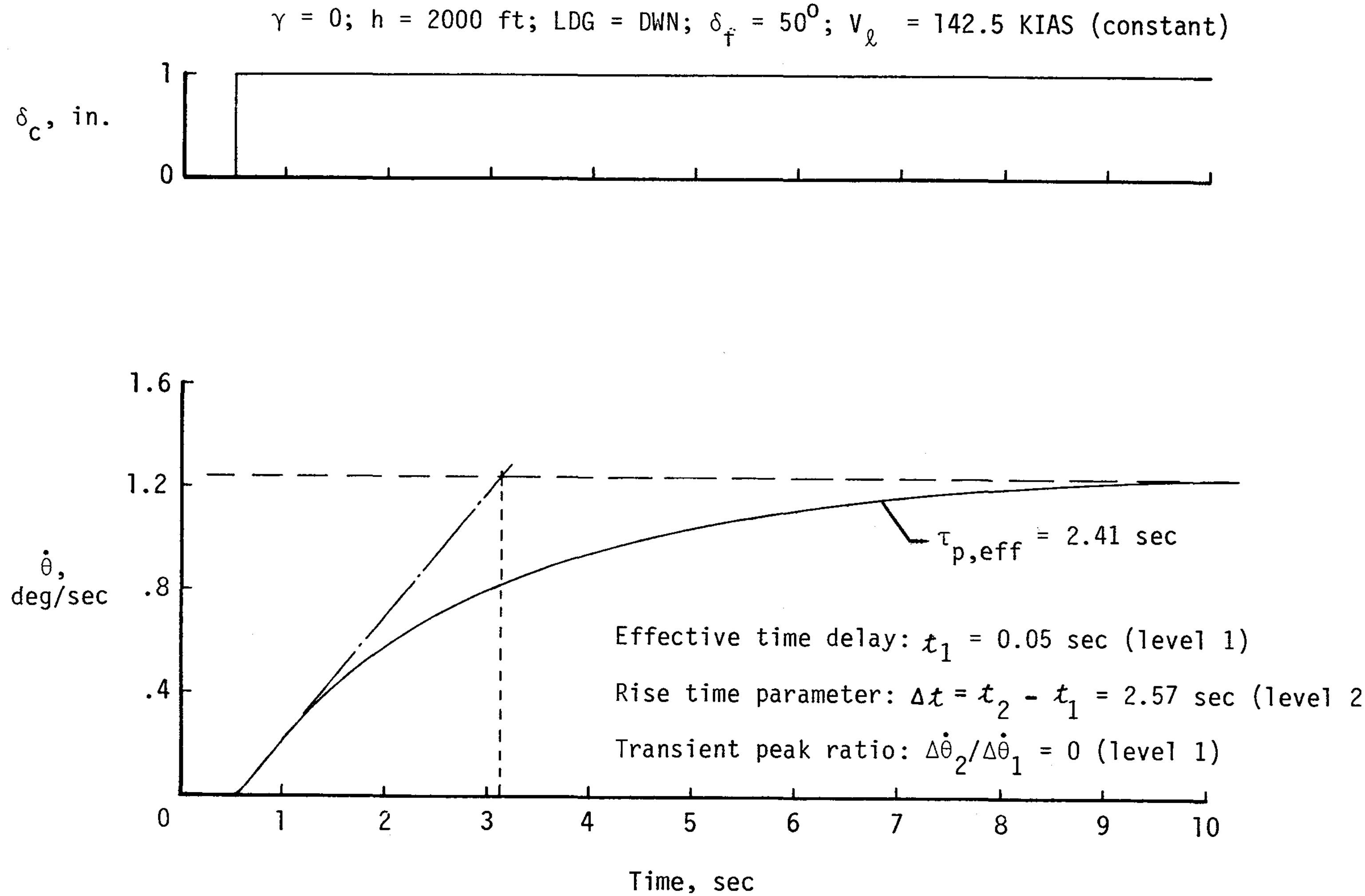
Figure 4. Langley Visual/Motion Simulator and instrument-panel display.



L-78-7794

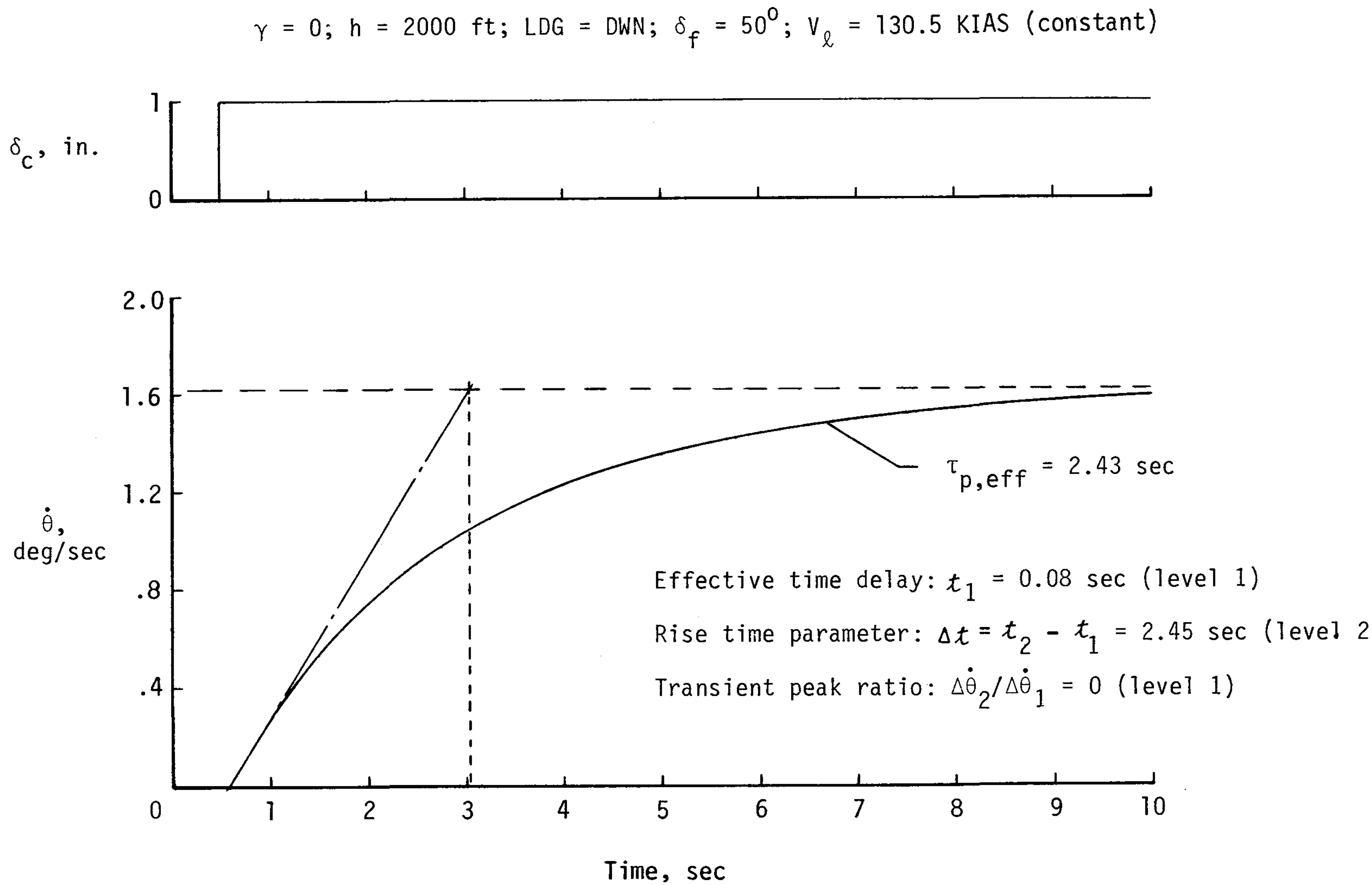
(b) Instrument panel.

Figure 4. Concluded.



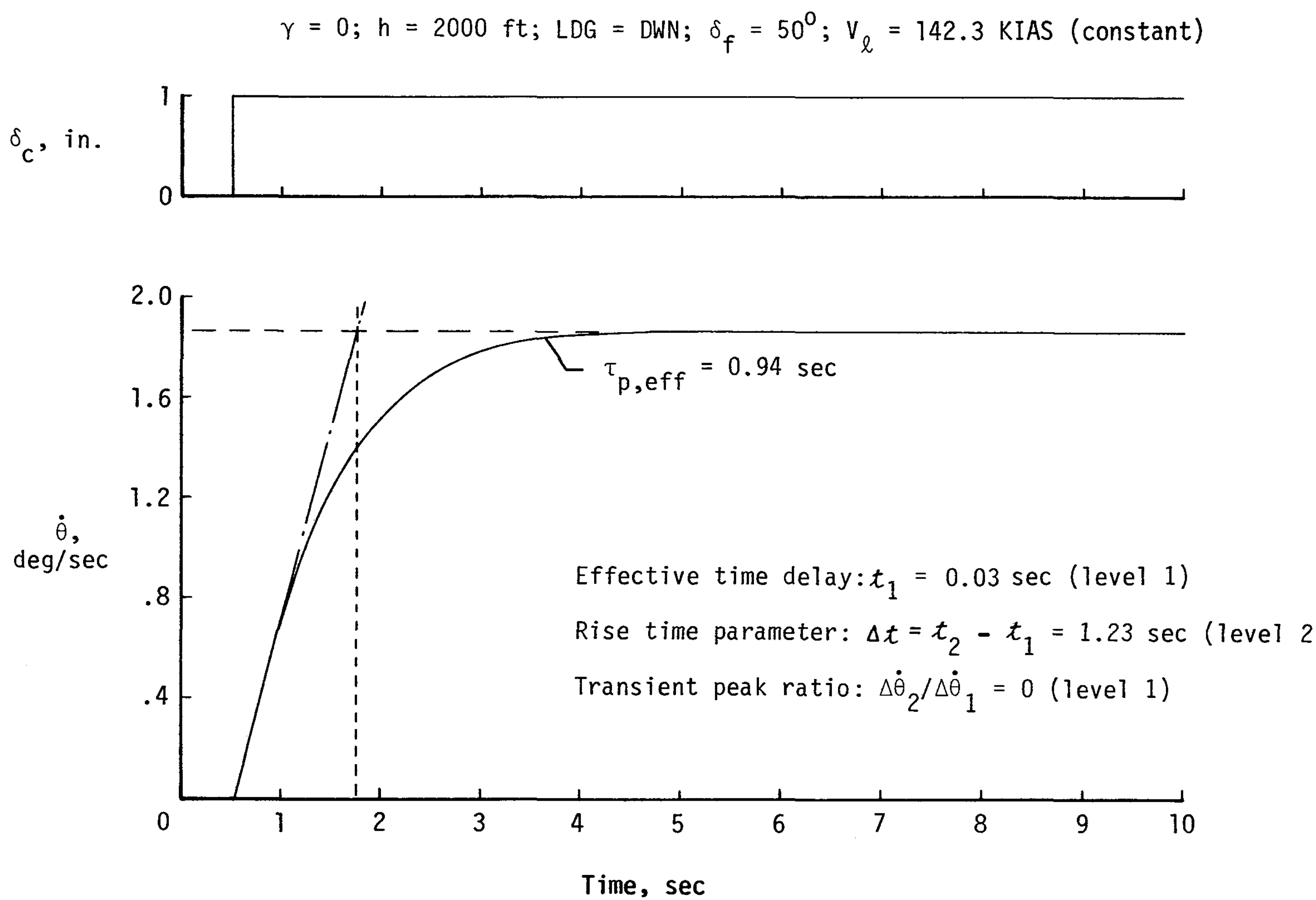
(a) Very large single-fuselage transport.

Figure 5. Pitch-rate response to column step input on unaugmented airplane.



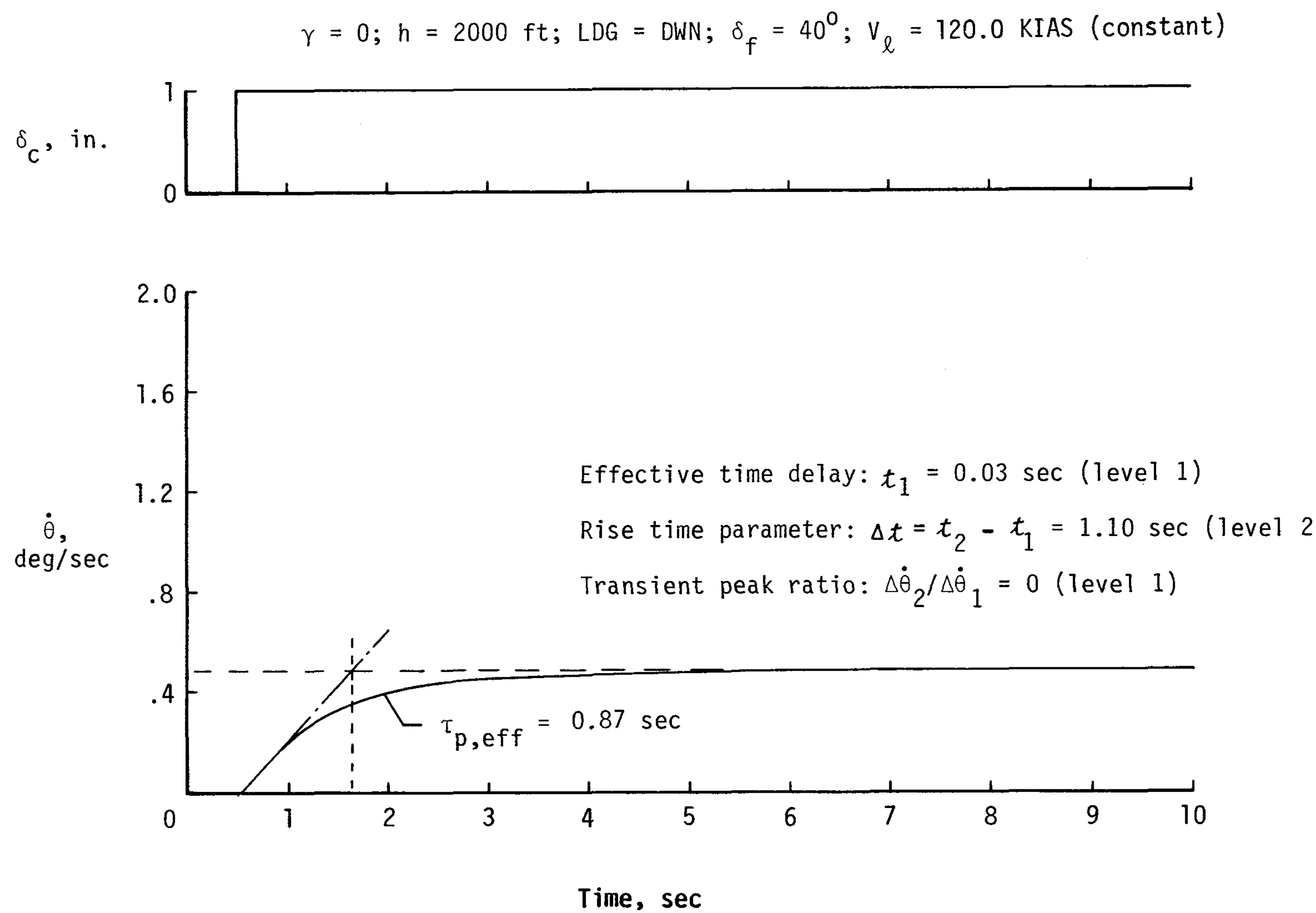
(b) Twin-fuselage transport.

Figure 5. Continued.



(c) Triple-fuselage transport.

Figure 5. Continued.



(d) Span-loader transport.

Figure 5. Concluded.

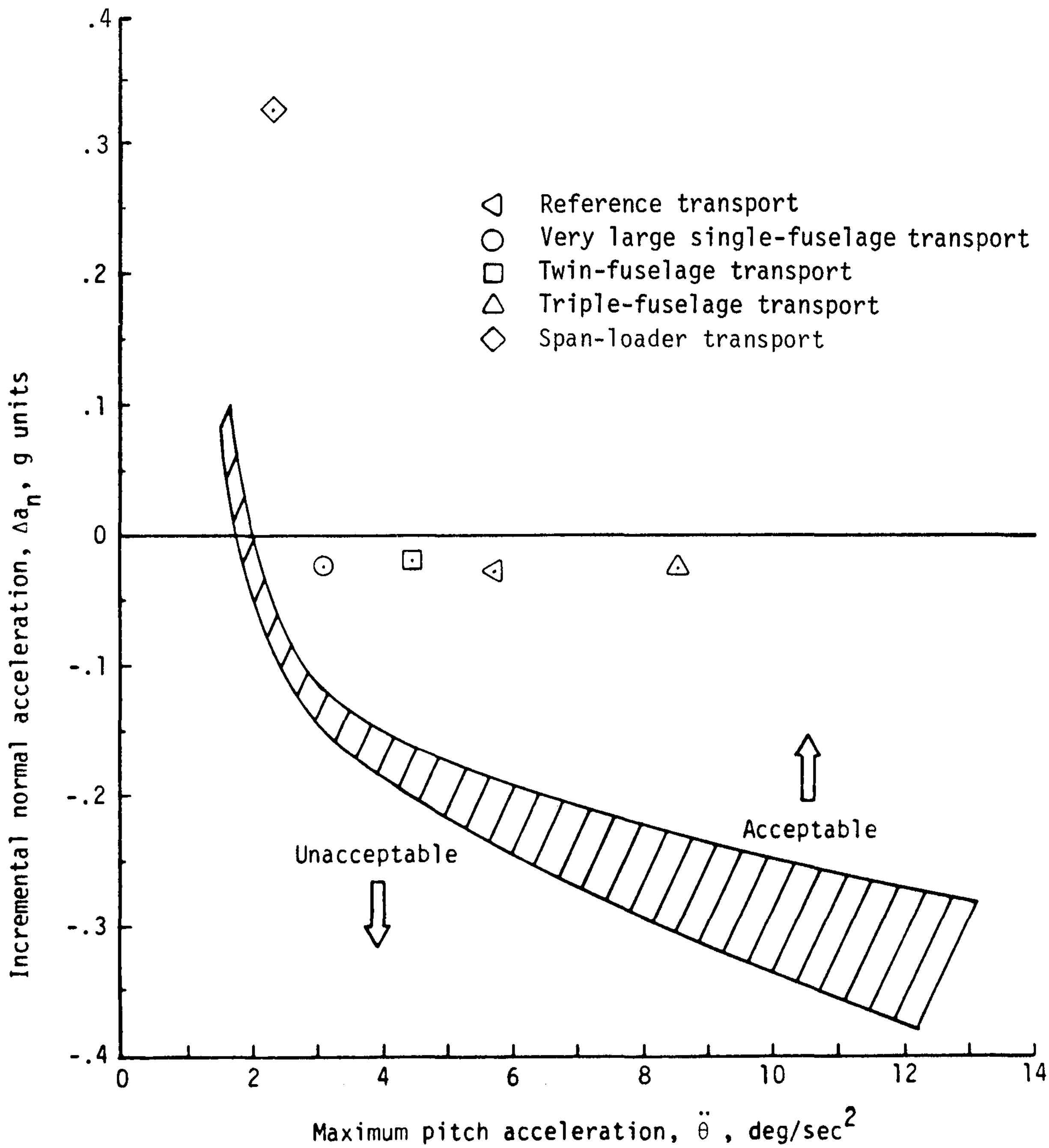
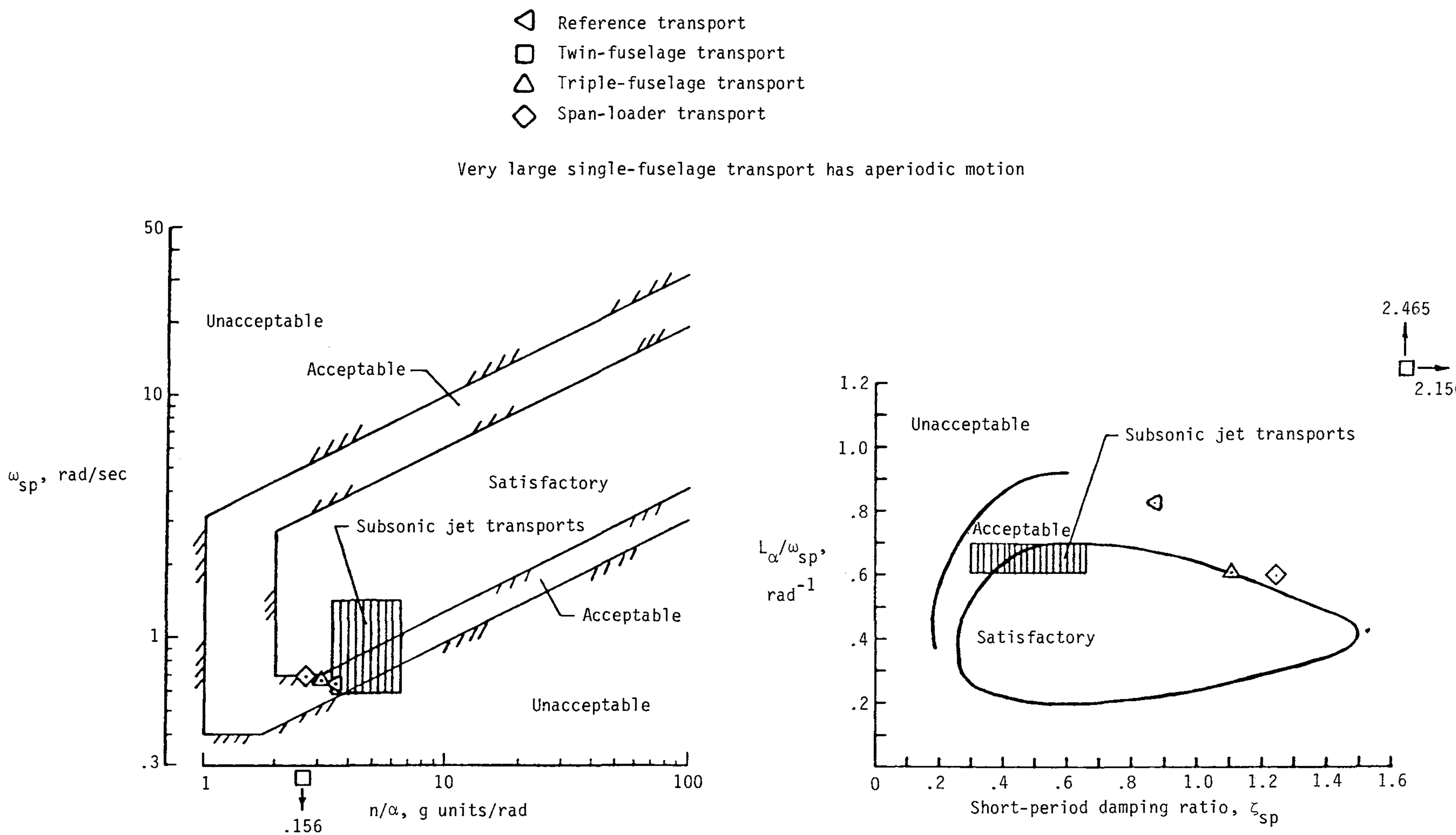


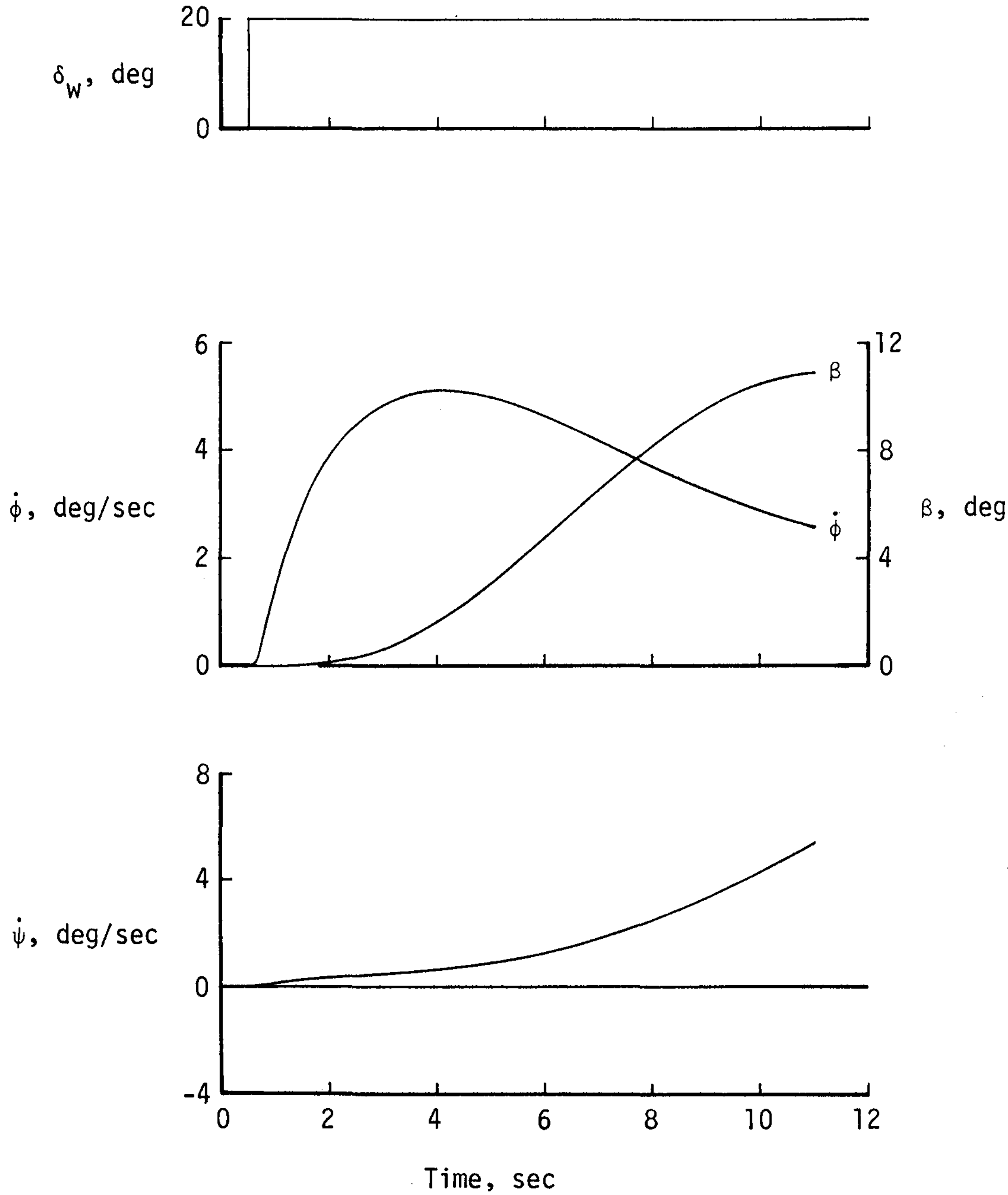
Figure 6. Comparison of longitudinal control characteristics of simulated transports with control requirements of reference 7.



(a) Criterion from reference 8.

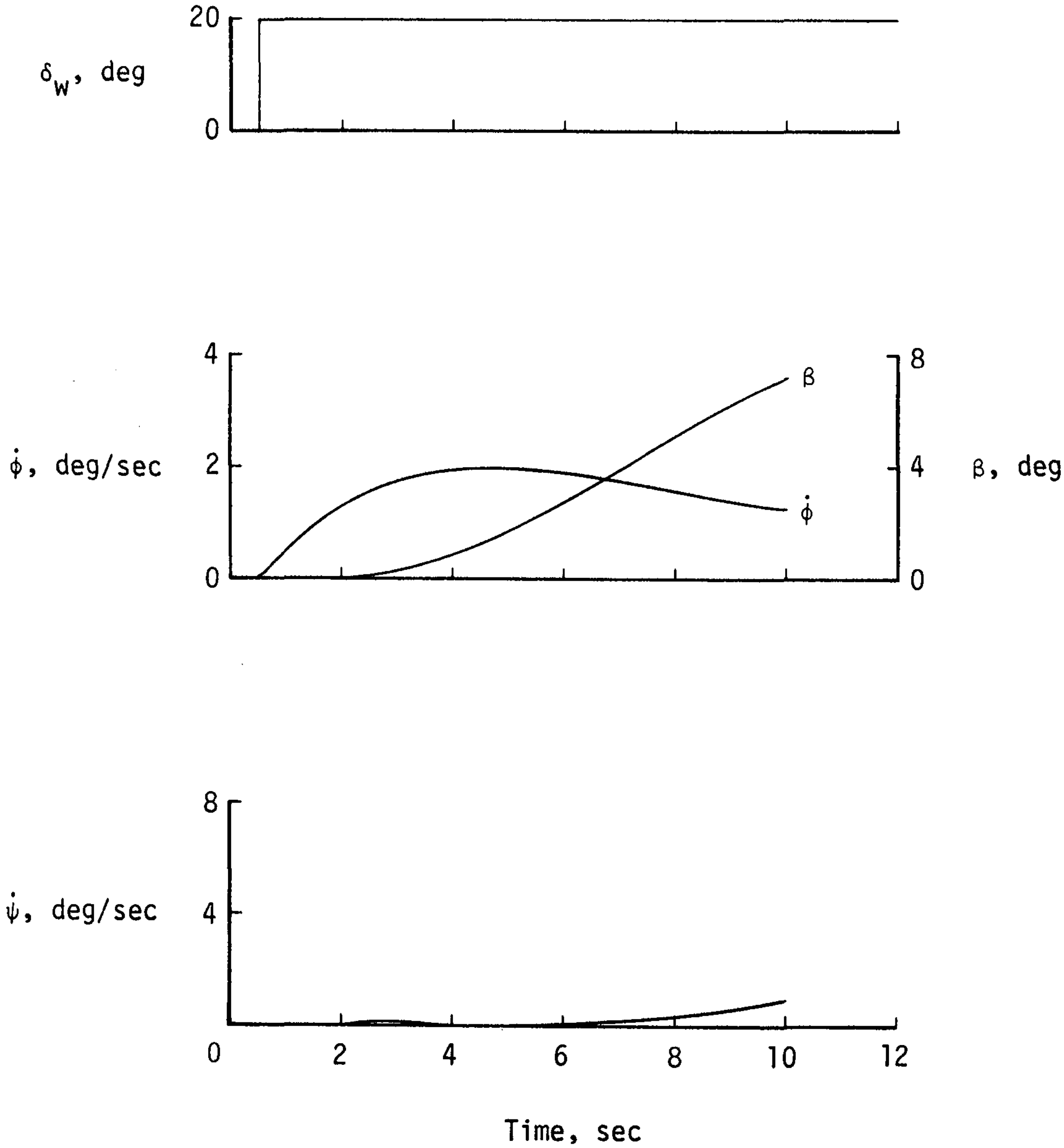
(b) Criterion from reference 9.

Figure 7. Comparison of unaugmented longitudinal characteristics of very large cargo transports simulated and reference transport with various handling qualities criteria.



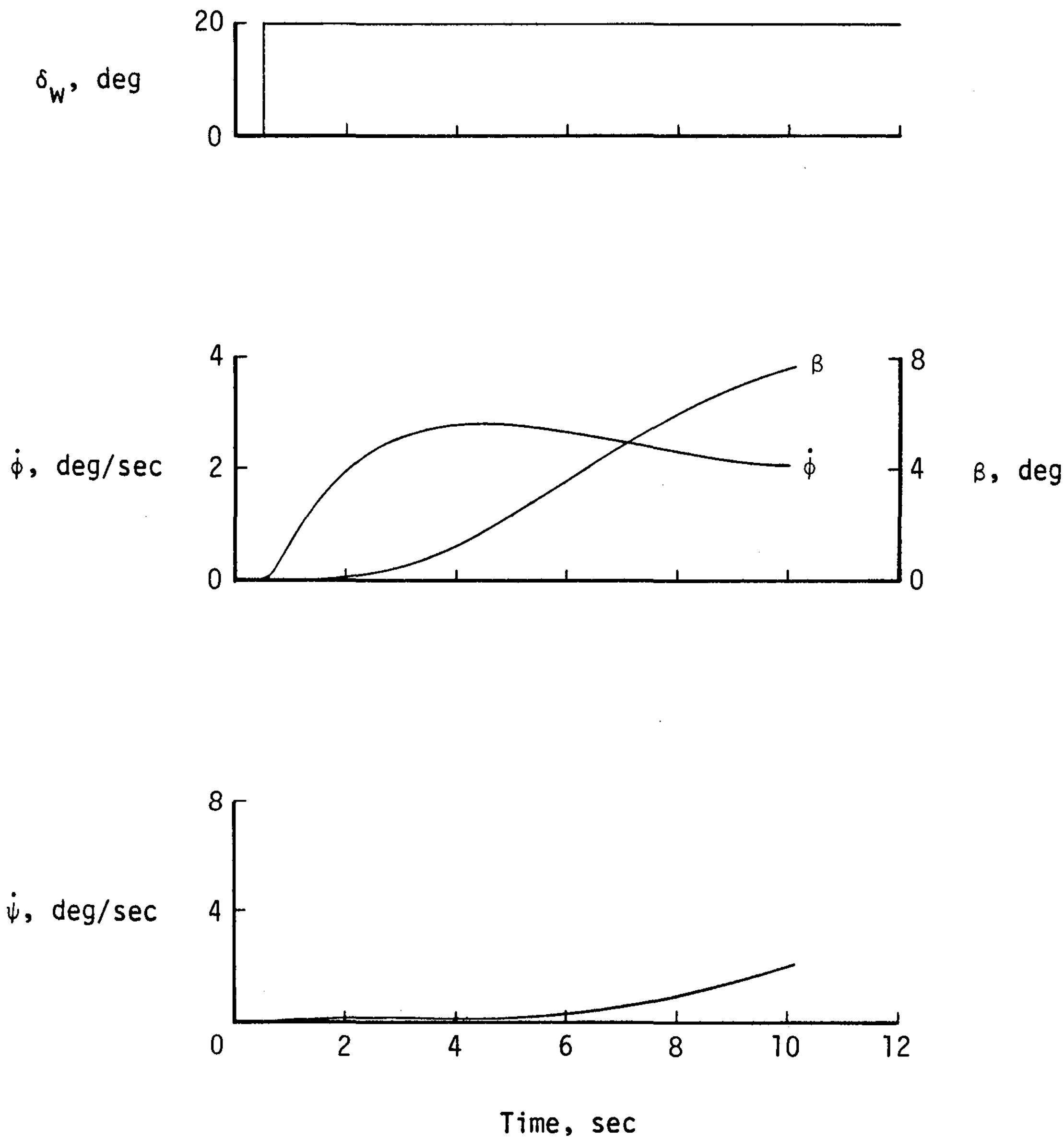
(a) Very large single-fuselage transport.

Figure 8. Lateral-directional response to a step wheel input on unaugmented airplane.



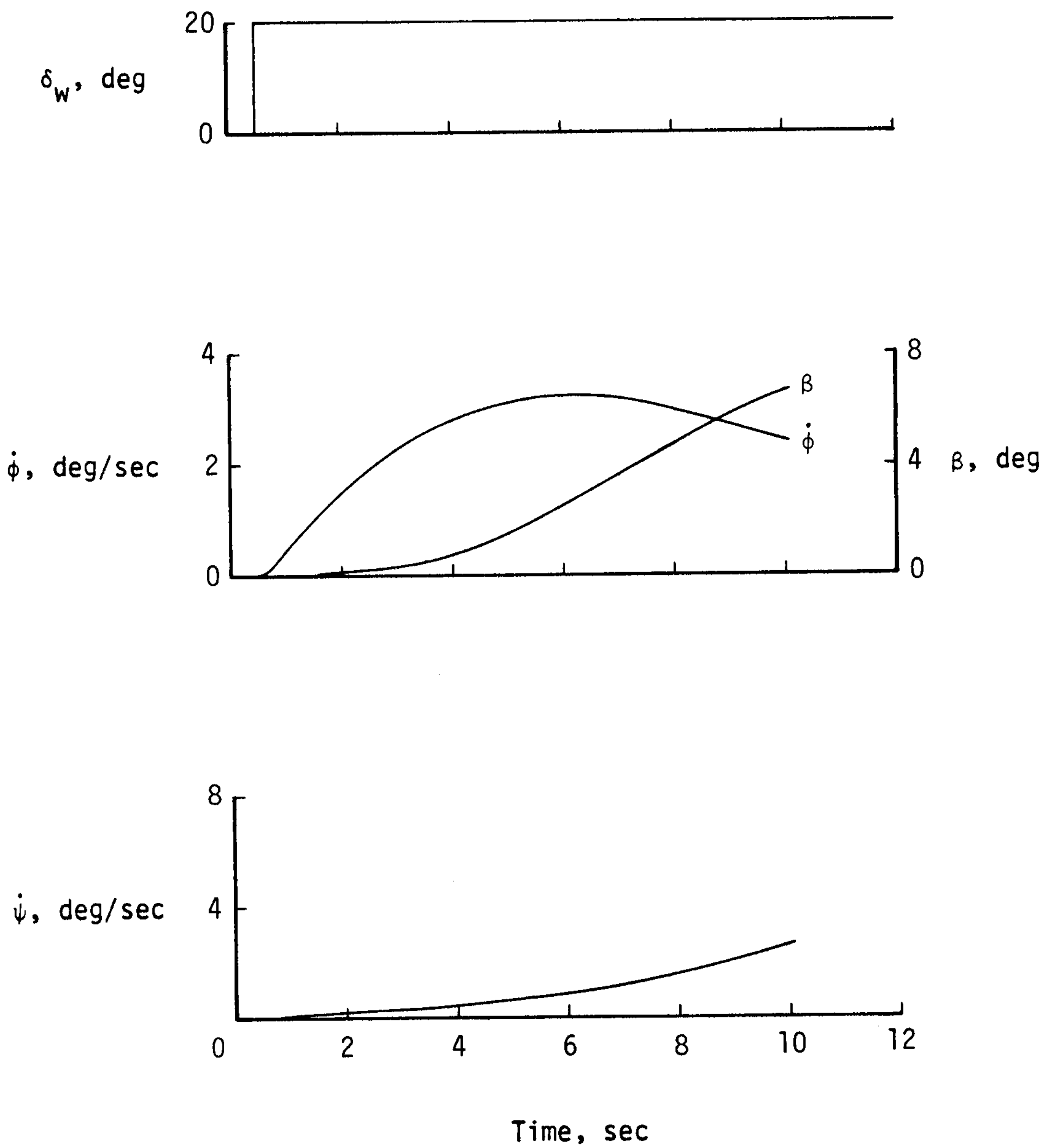
(b) Twin-fuselage transport.

Figure 8. Continued.



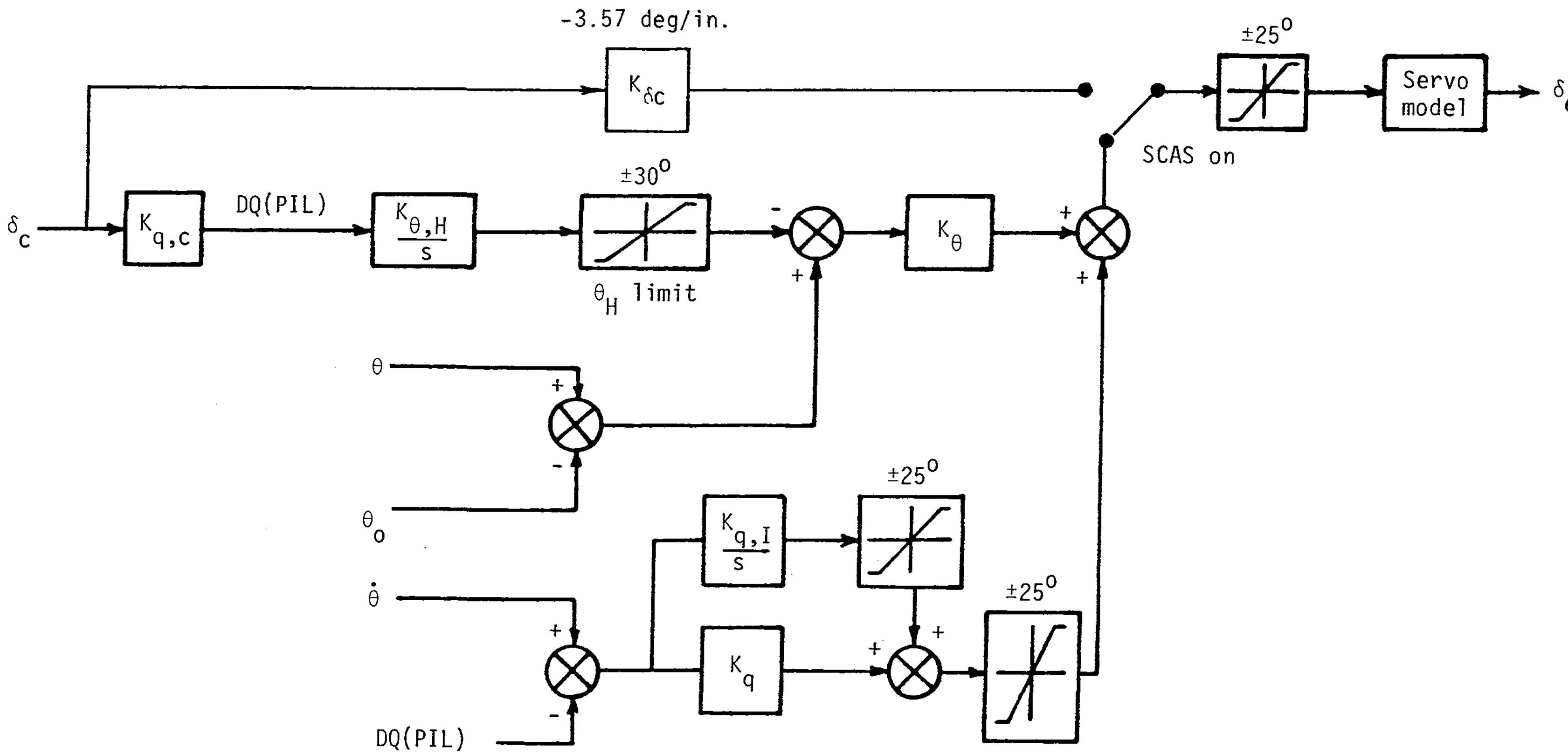
(c) Triple-fuselage transport.

Figure 8. Continued.



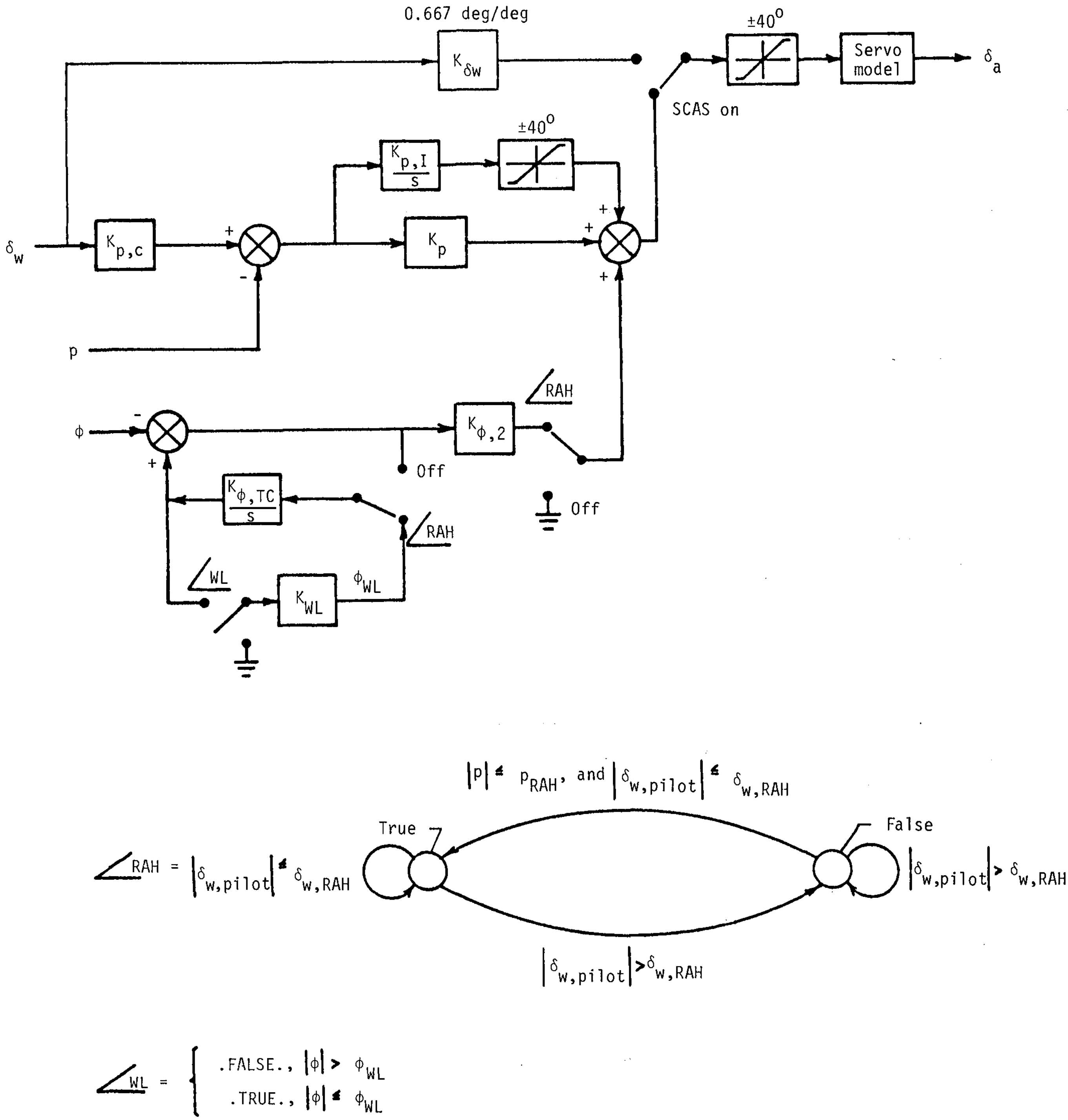
(d) Span-loader transport.

Figure 8. Concluded.



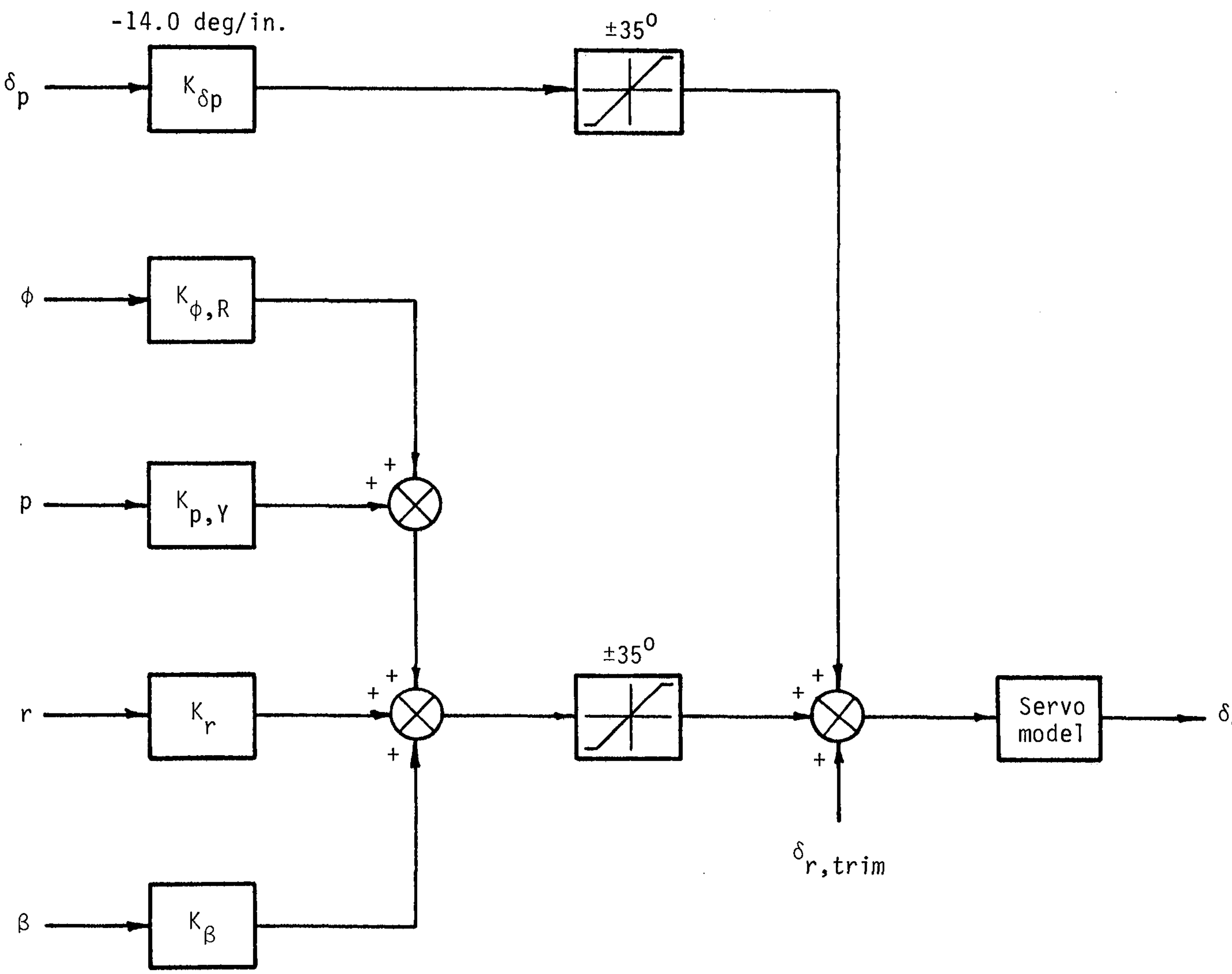
(a) Longitudinal (pitch) control system.

Figure 9. Normal operational stability and control augmentation system (SCAS). $\tau_{\text{servo}} = 0.1$ sec. Flight-control-system gains are presented in table VI.



(b) Lateral (roll) control system with switching logic.

Figure 9. Continued.



(c) Directional (yaw) control system.

Figure 9. Concluded.

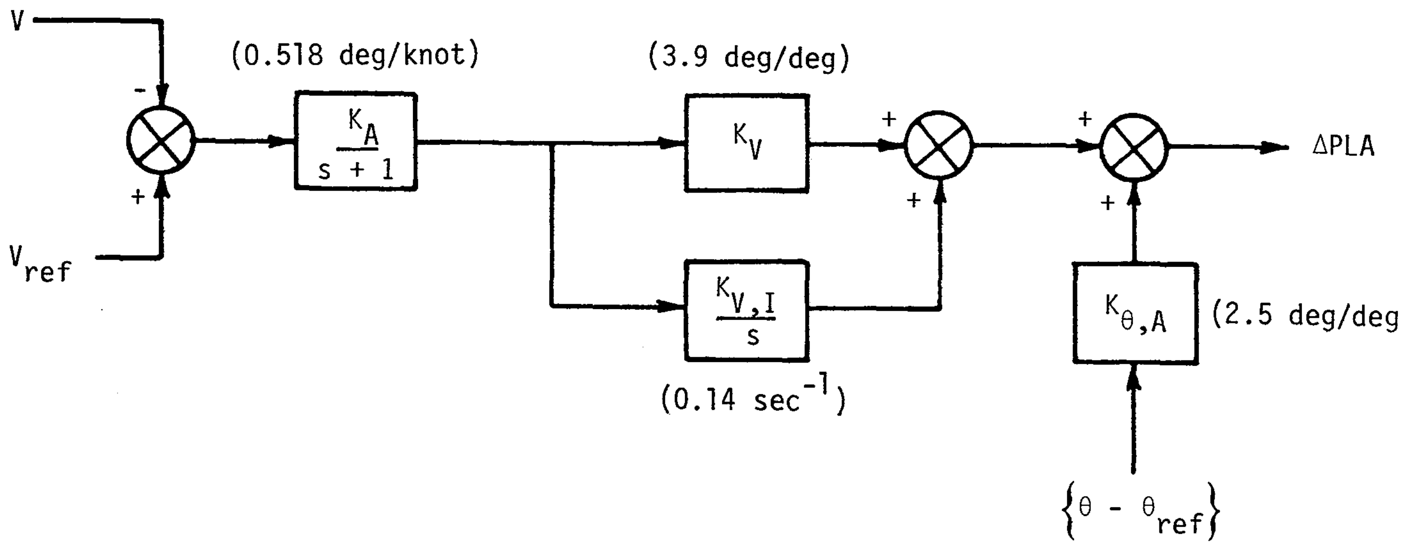
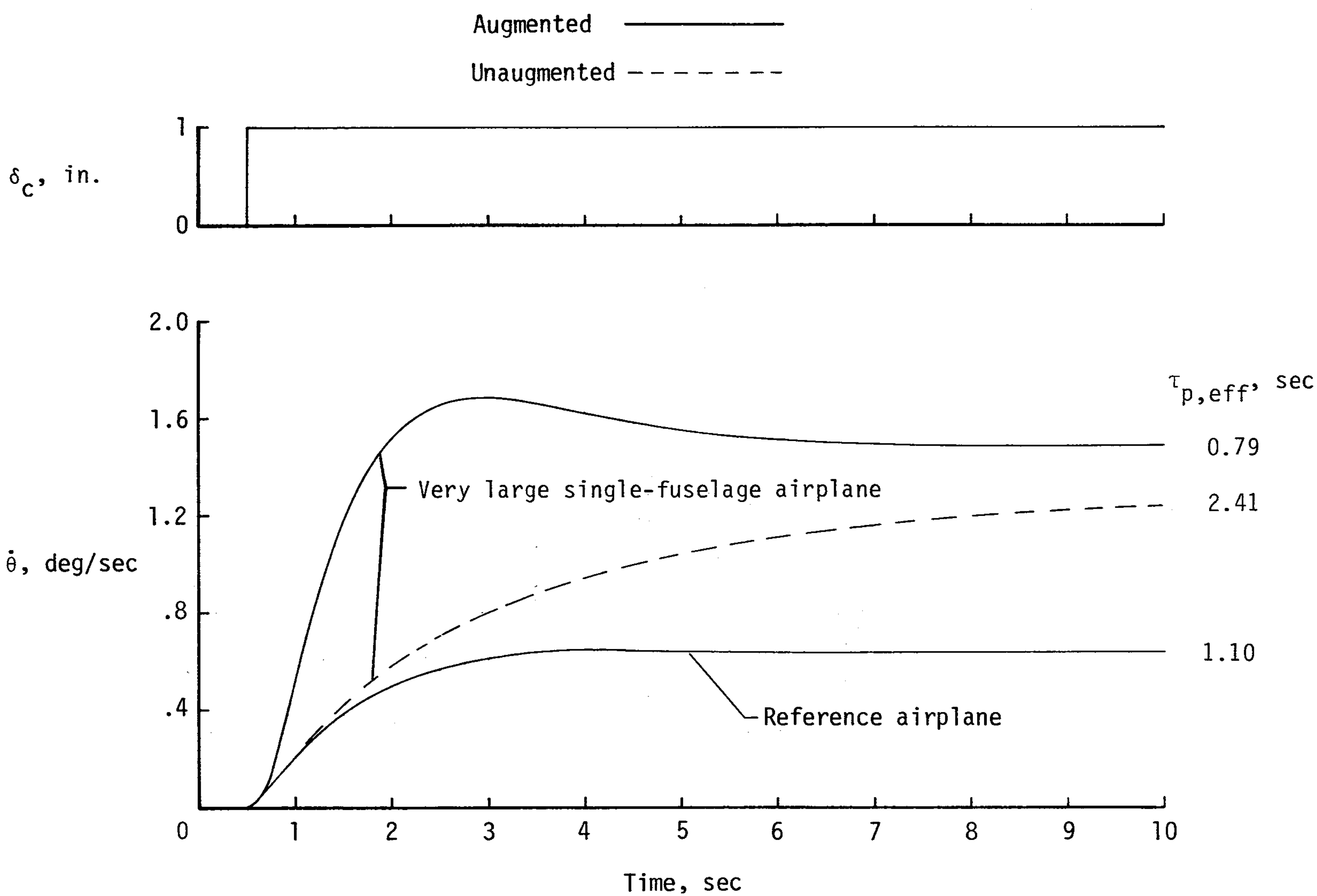
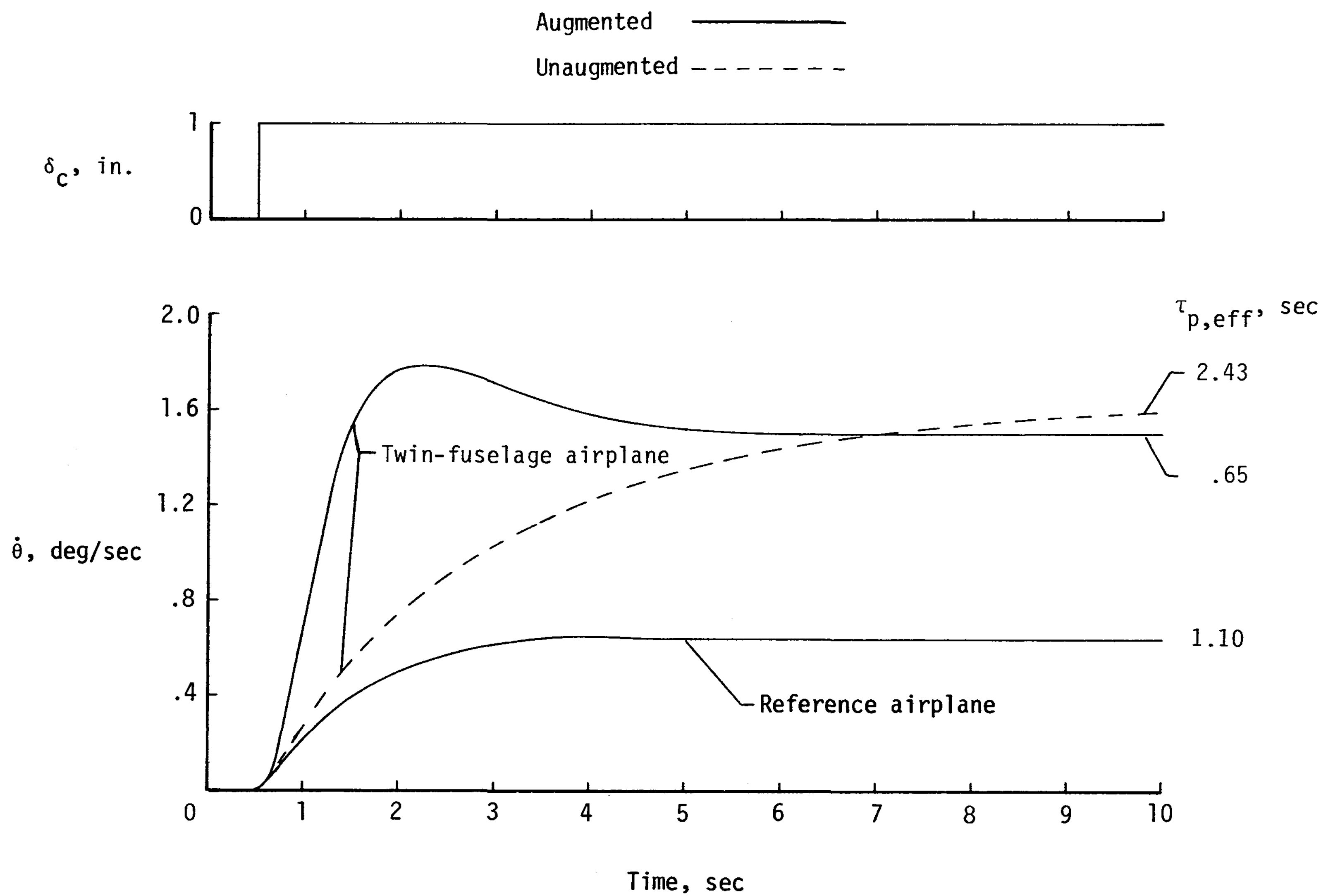


Figure 10. Block diagram of autothrottle for all configurations in figure 1. Gains are indicated in parentheses.



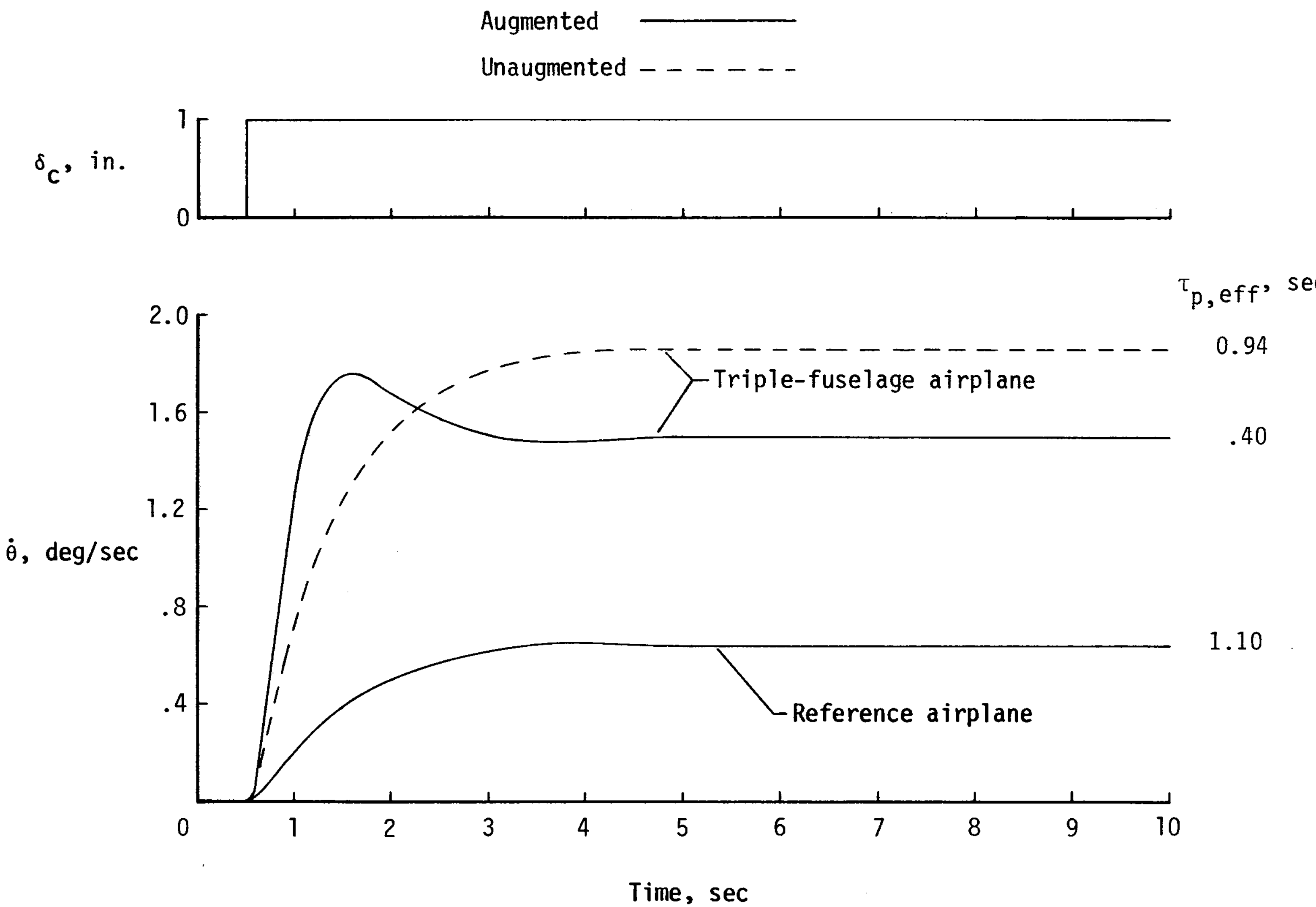
(a) Comparison between simulated reference and very large single-fuselage transports.

Figure 11. Pitch-rate response of augmented and unaugmented airplanes.



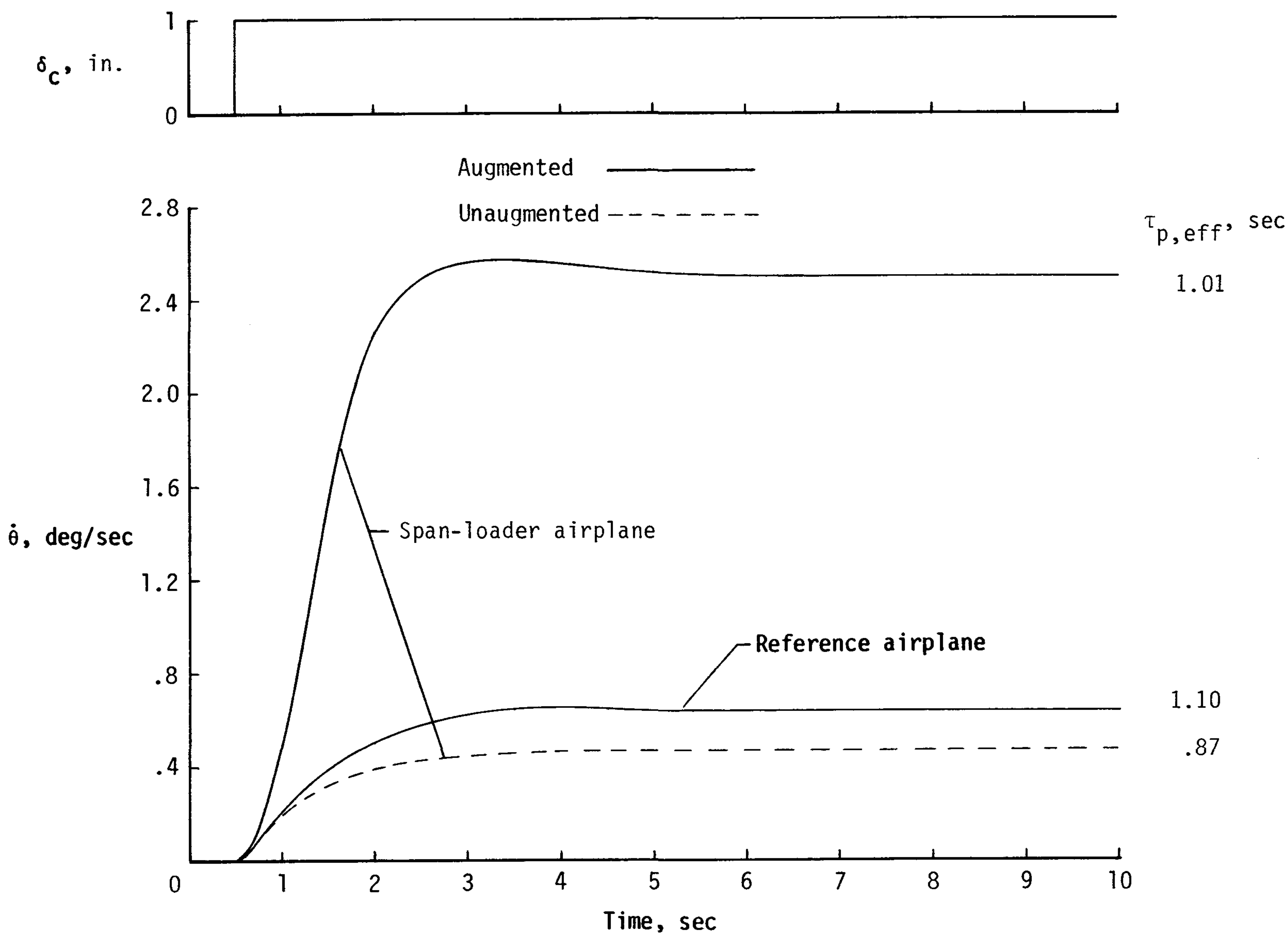
(b) Comparison between simulated reference and twin-fuselage transports.

Figure 11. Continued.



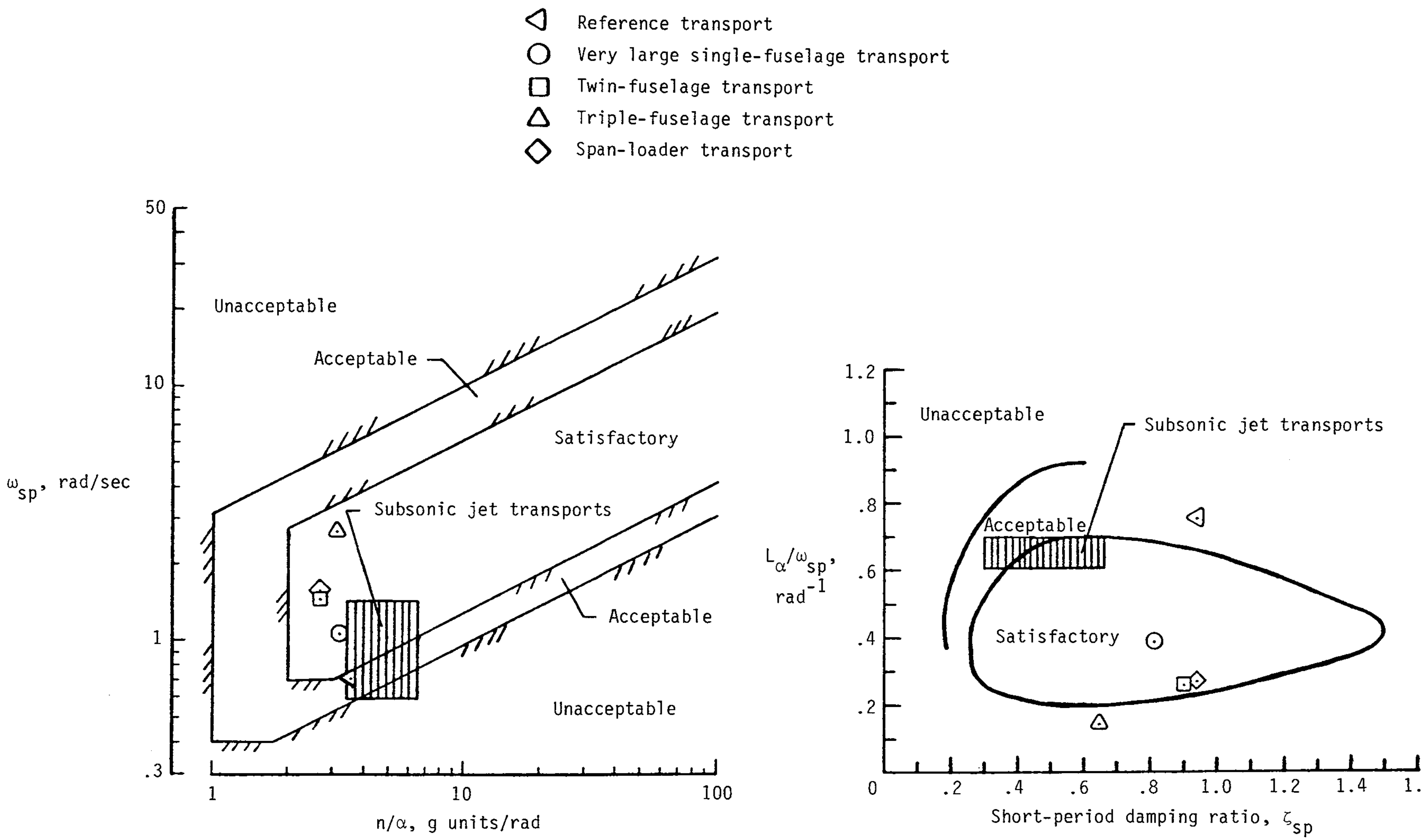
(c) Comparison between simulated reference and triple-fuselage transports.

Figure 11. Continued.



(d) Comparison between simulated reference and span-loader transports.

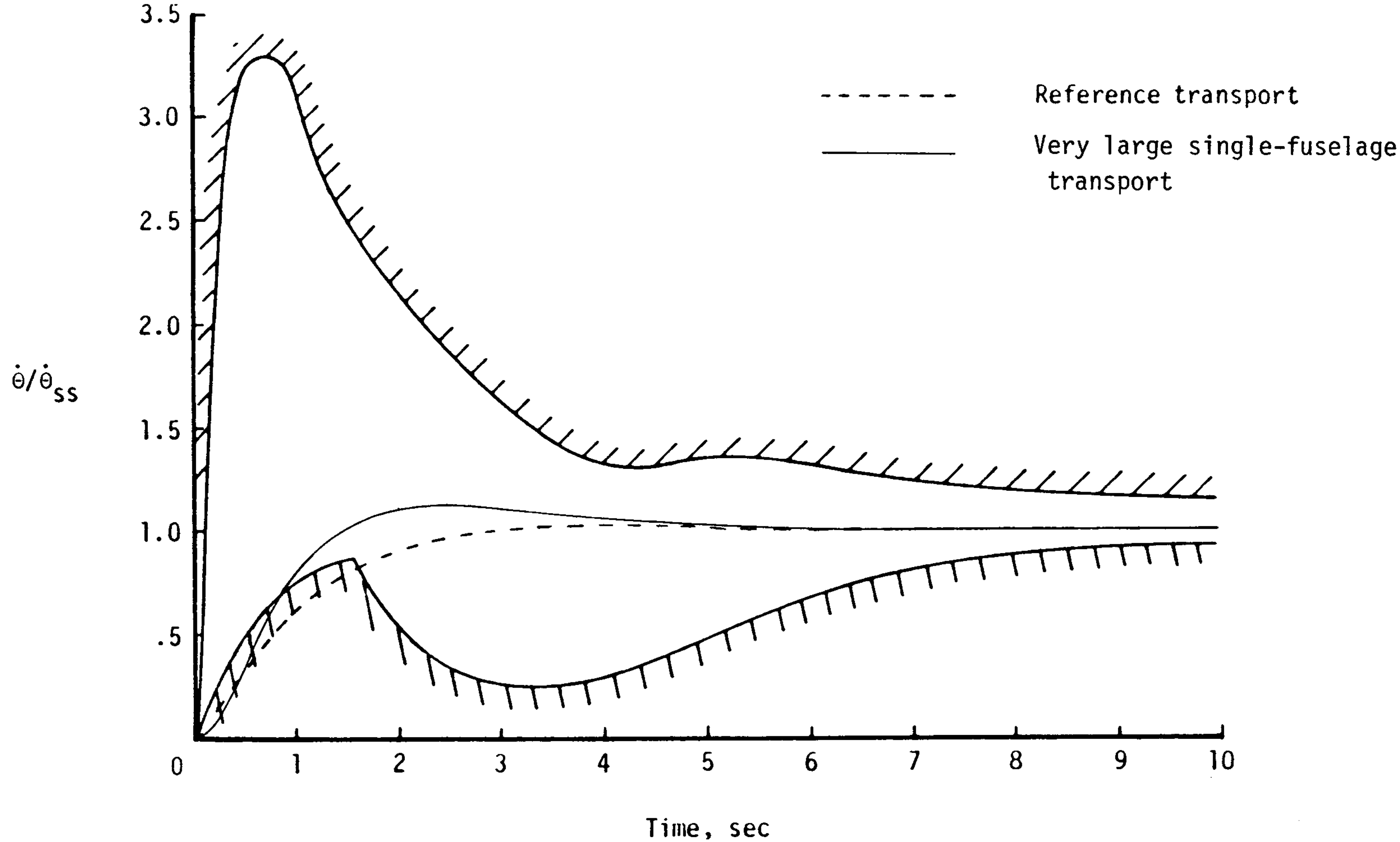
Figure 11. Concluded.



(a) Short-period frequency criterion of reference 8.

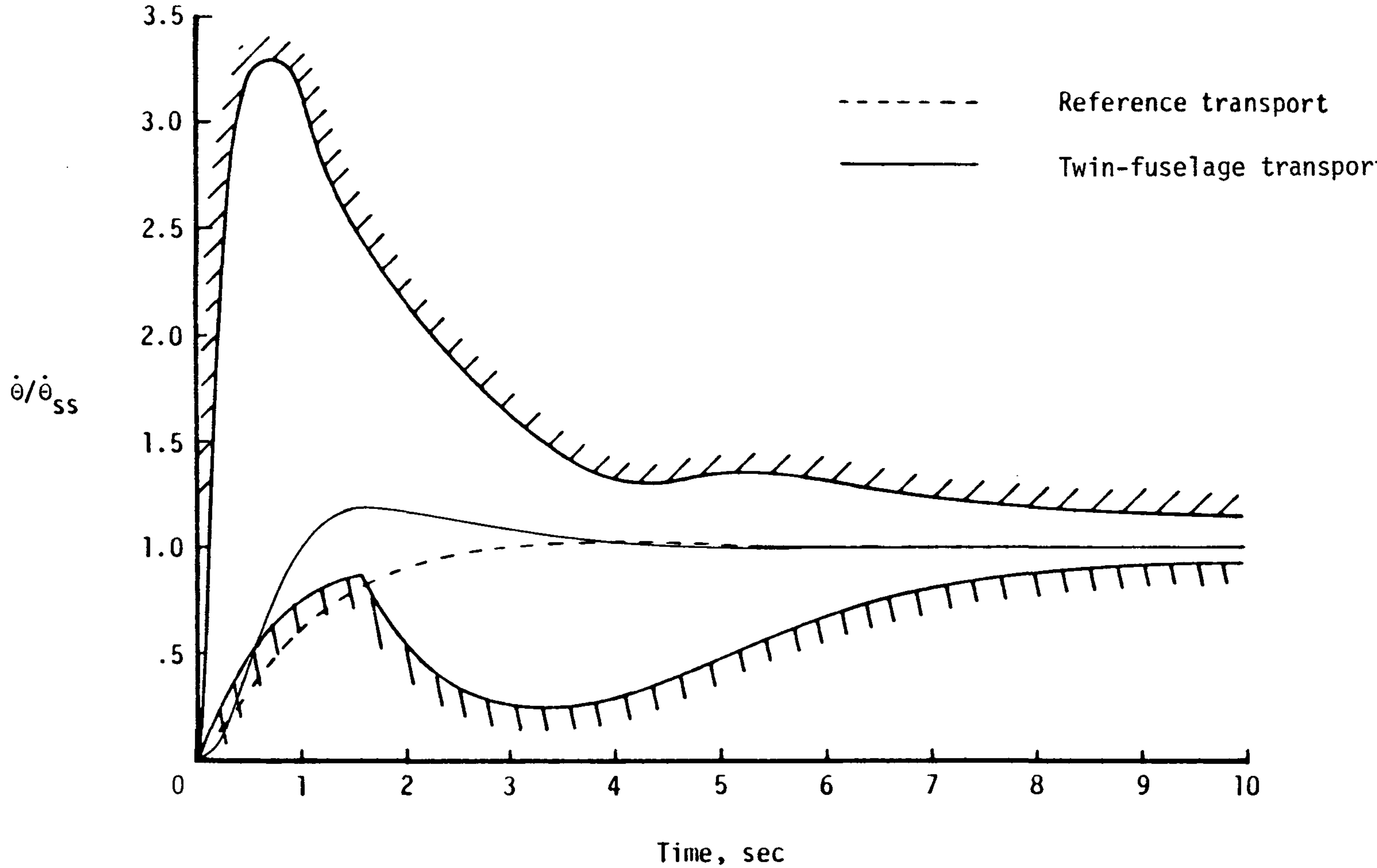
(b) Longitudinal handling qualities criterion of reference 9.

Figure 12. Comparison of various augmented simulated transport airplanes with short-period criteria of references 8 and 9.



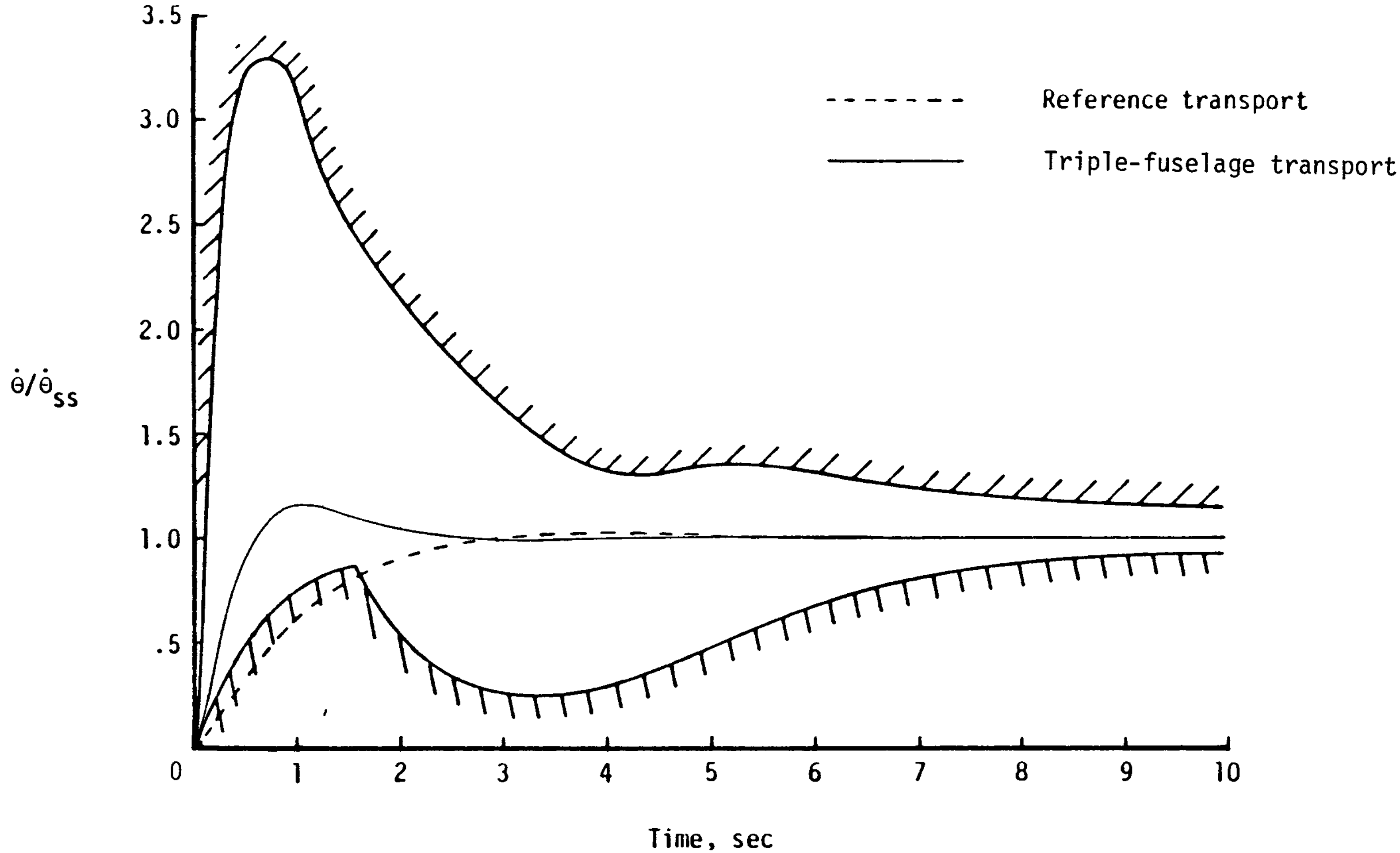
(a) Comparison between augmented simulated reference and augmented very large single-fuselage transports.

Figure 13. Low-speed pitch-rate response criterion of reference 10. Boundaries for normal operation (PR $\leq$ 3.5).



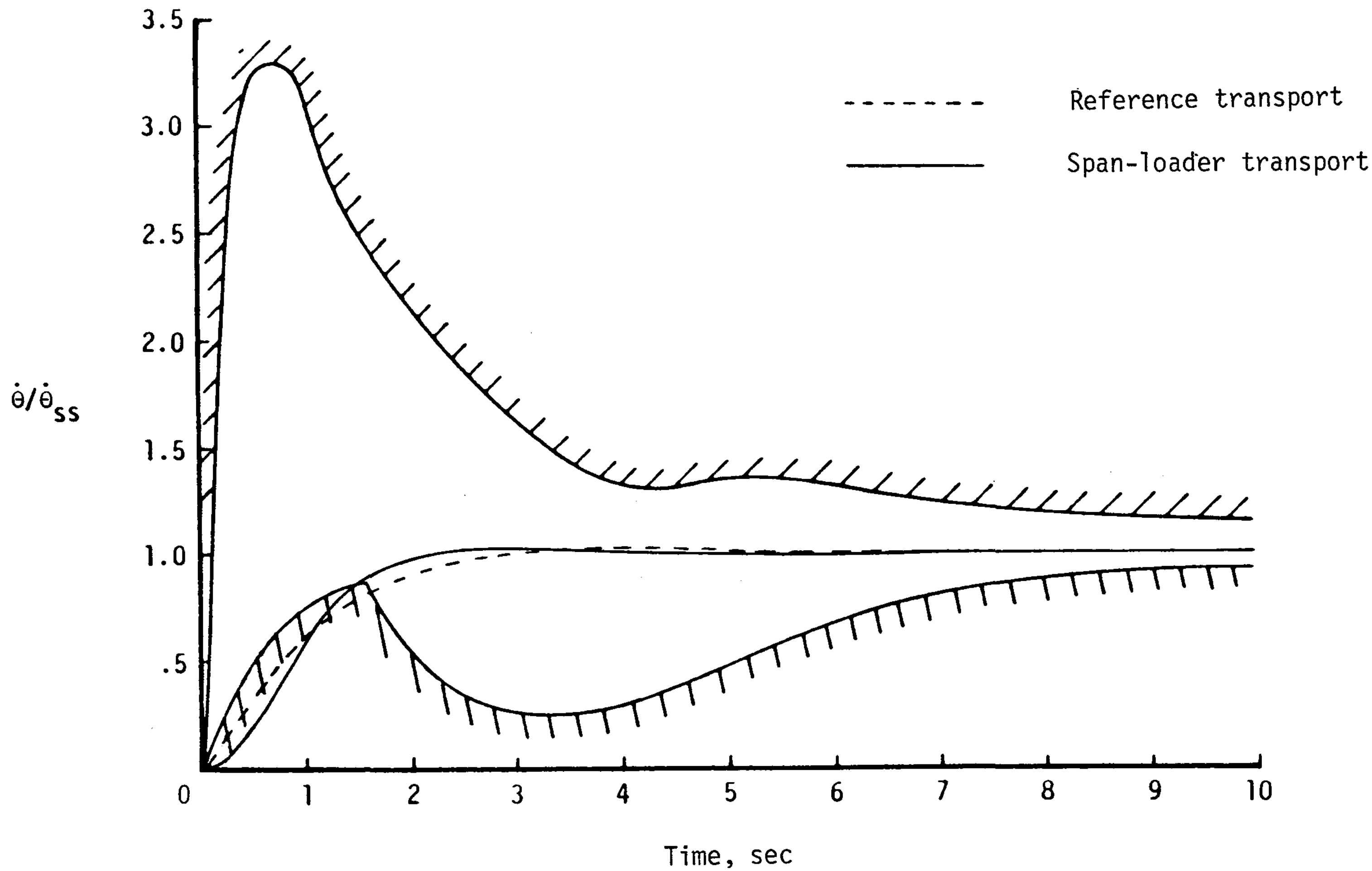
(b) Comparison between augmented simulated reference and augmented twin-fuselage transports.

Figure 13. Continued.



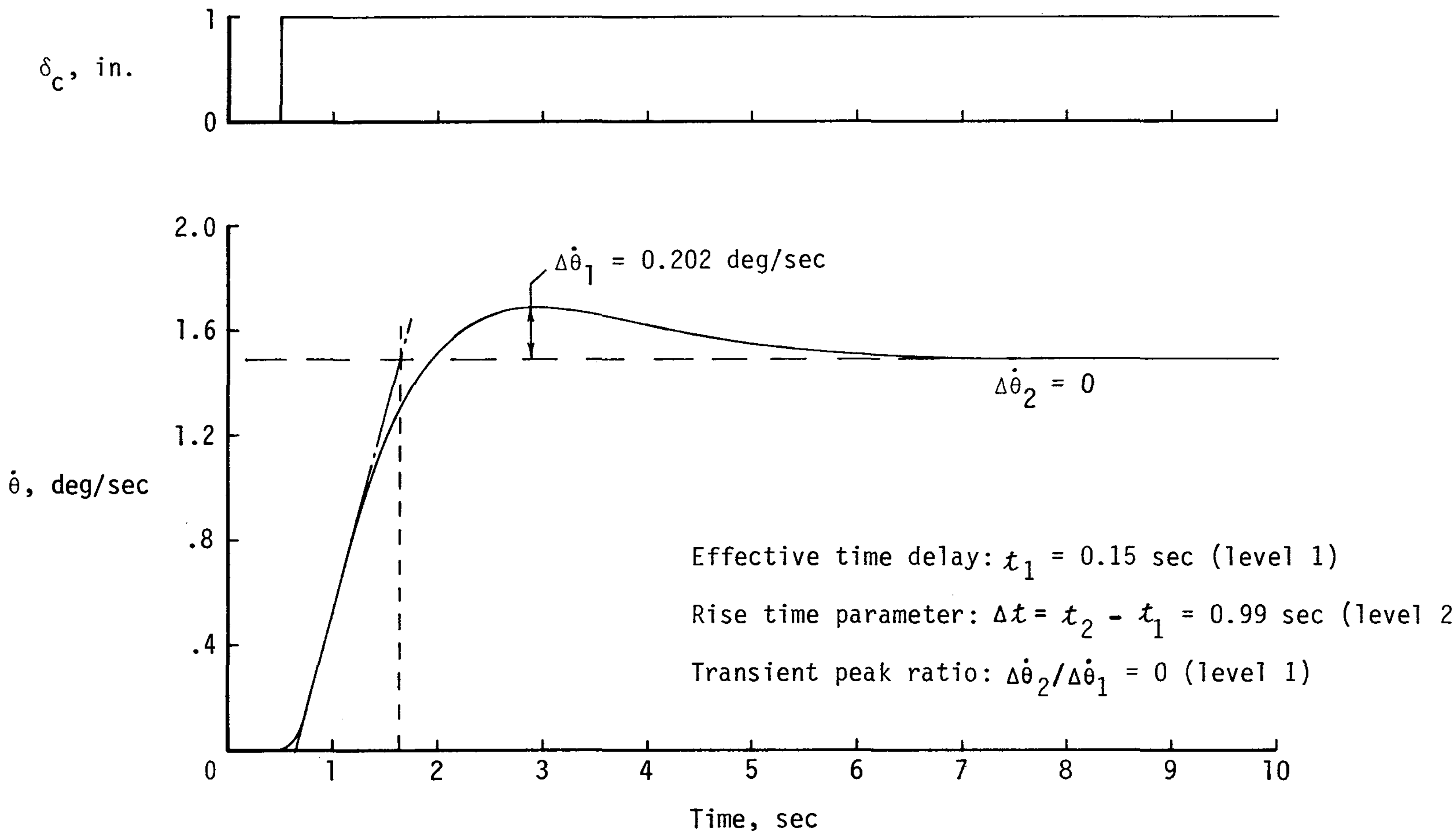
(c) Comparison between augmented simulated reference and augmented triple-fuselage transports.

Figure 13. Continued.



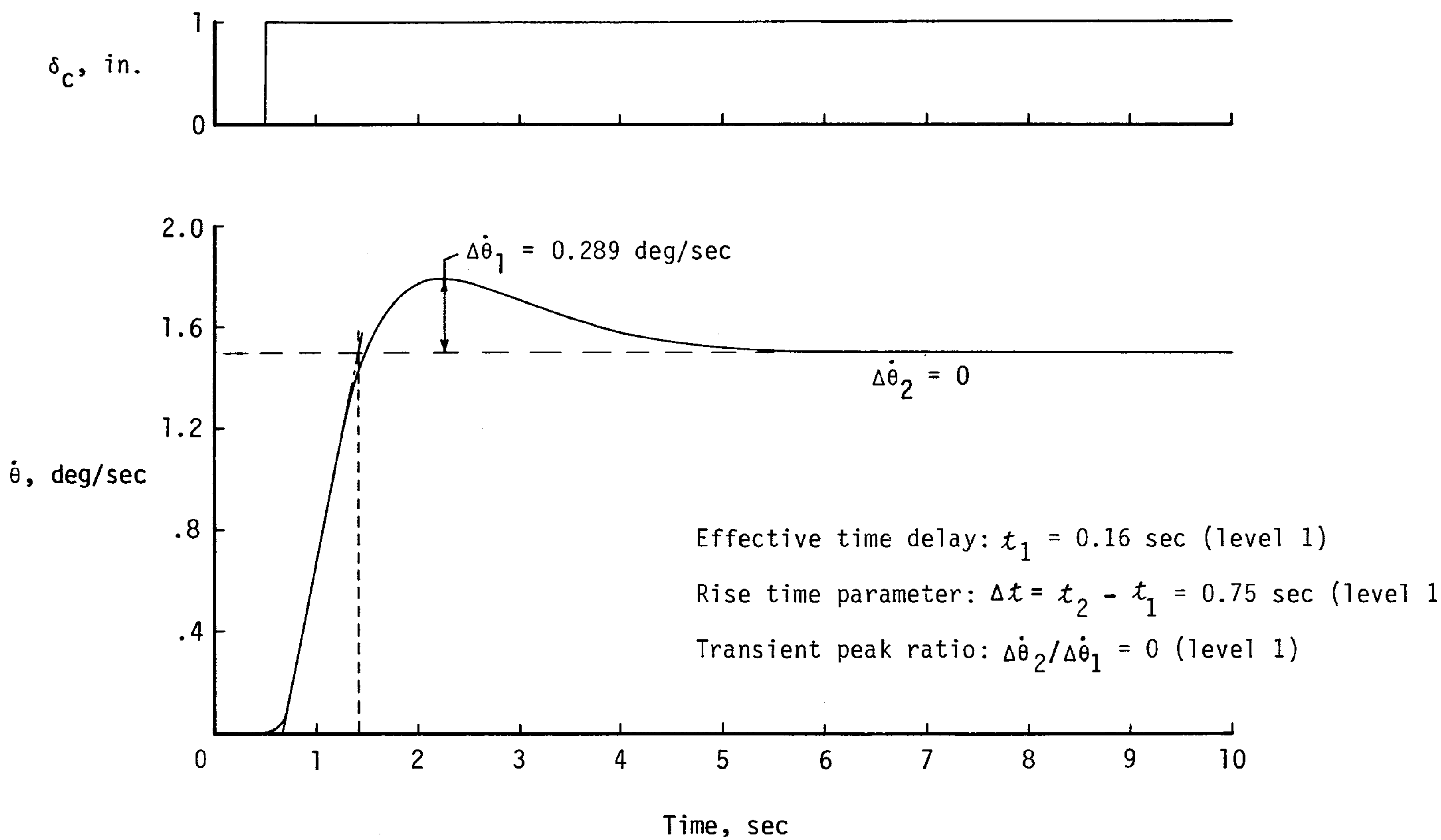
(d) Comparison between augmented simulated reference and augmented span-loader transports.

Figure 13. Concluded.



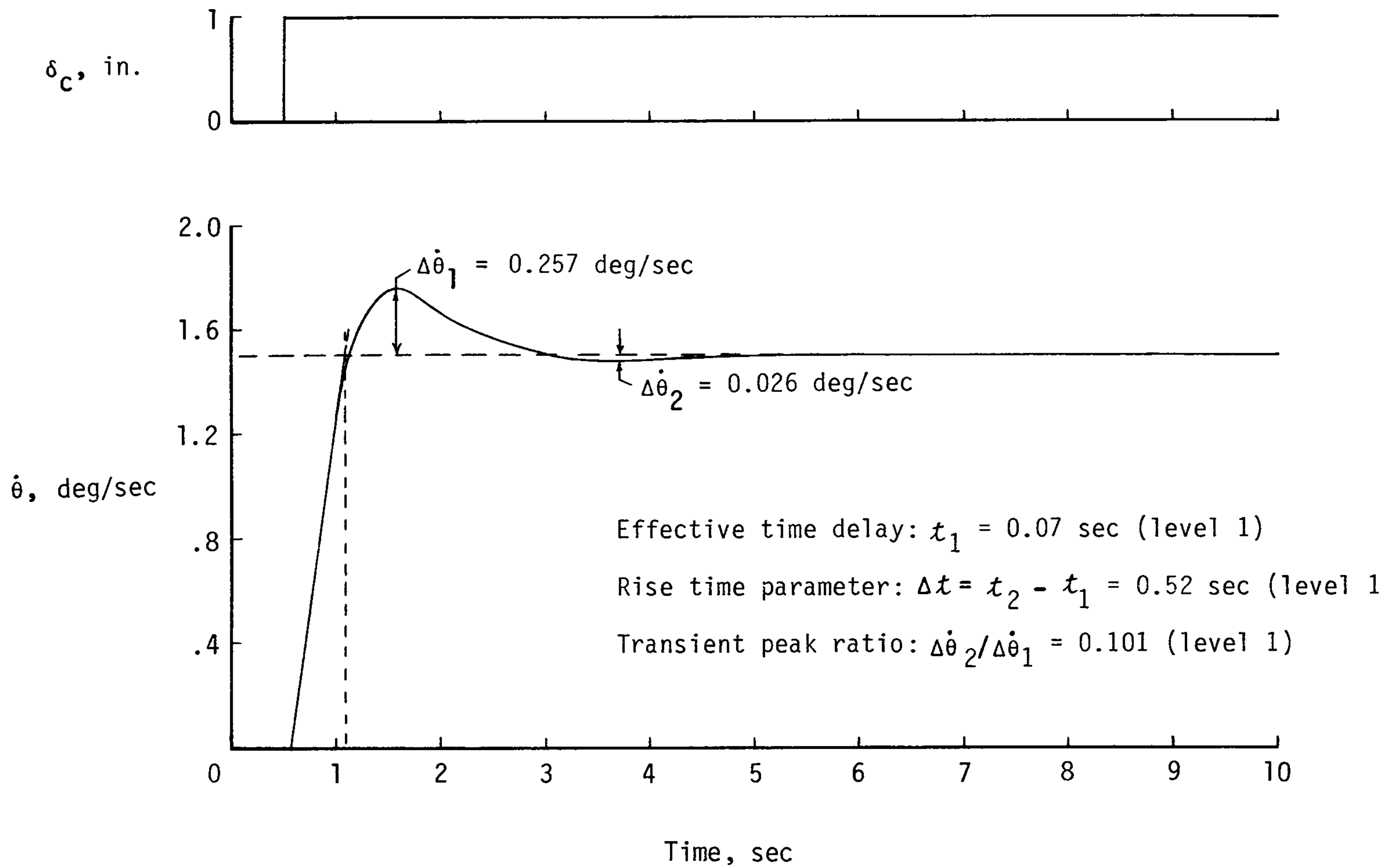
(a) Very large single-fuselage transport.

Figure 14. Pitch-rate response to column step input on augmented airplane. Criteria from reference 6.



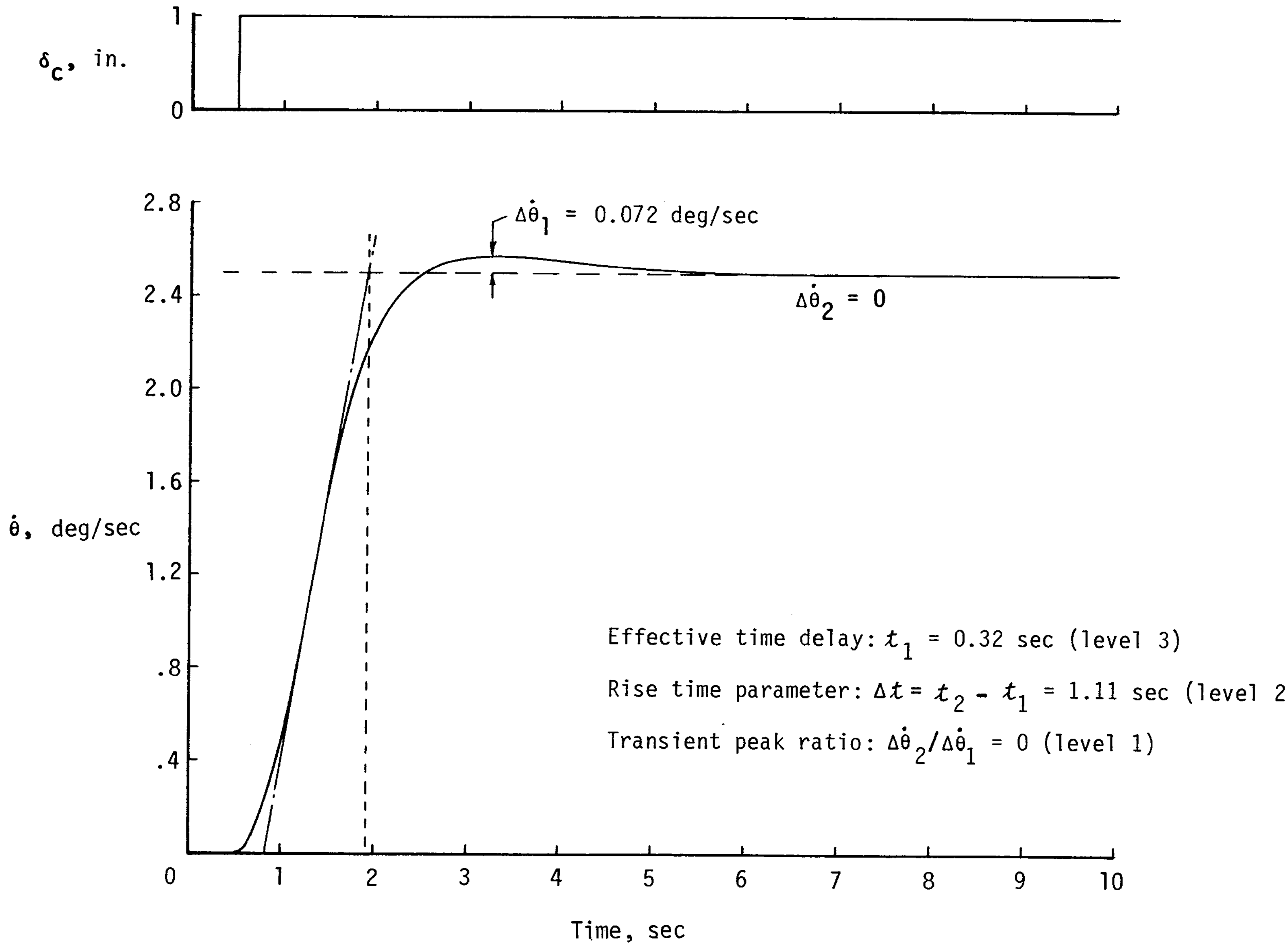
(b) Twin-fuselage transport.

Figure 14. Continued.



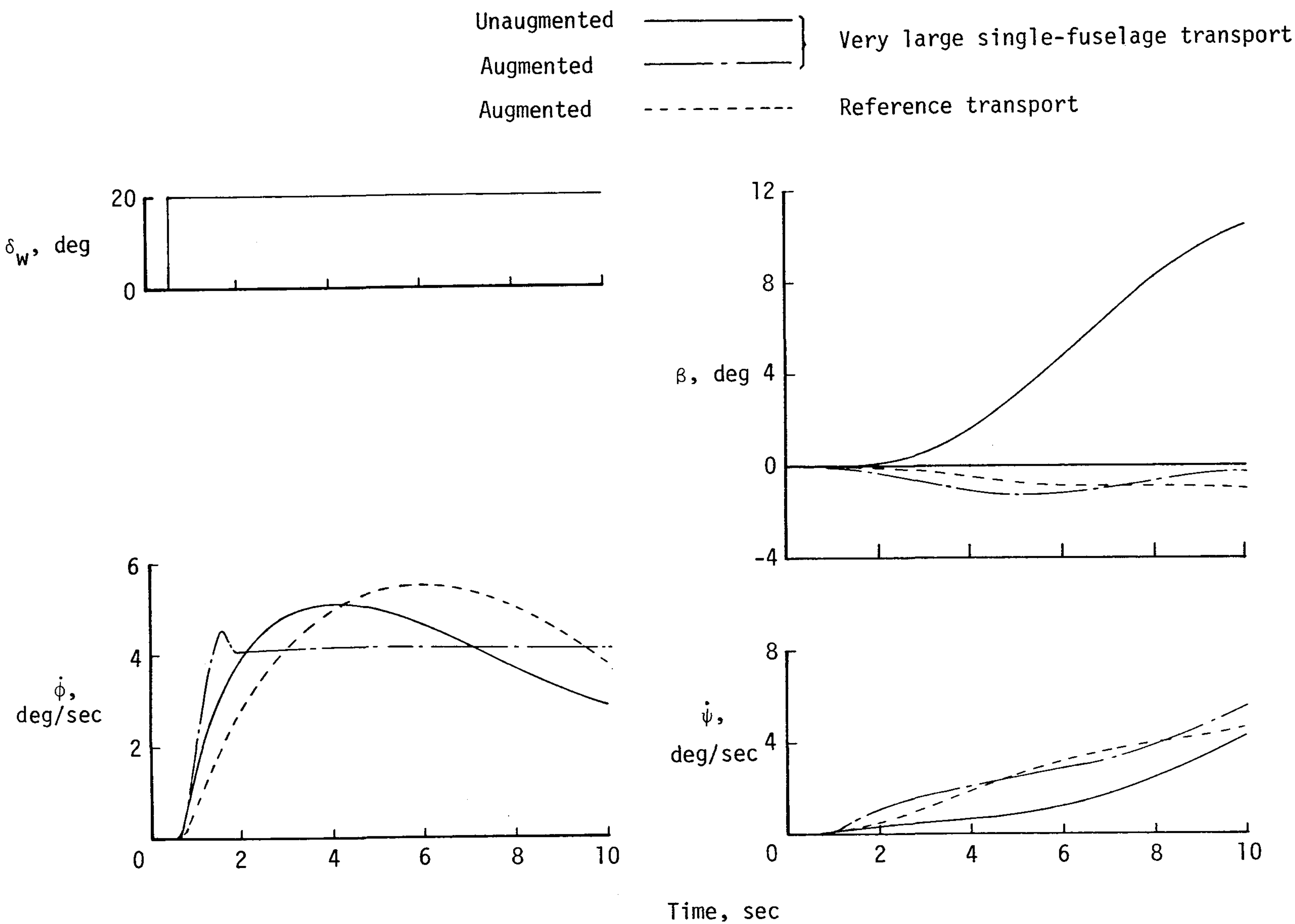
(c) Triple-fuselage transport.

Figure 14. Continued.



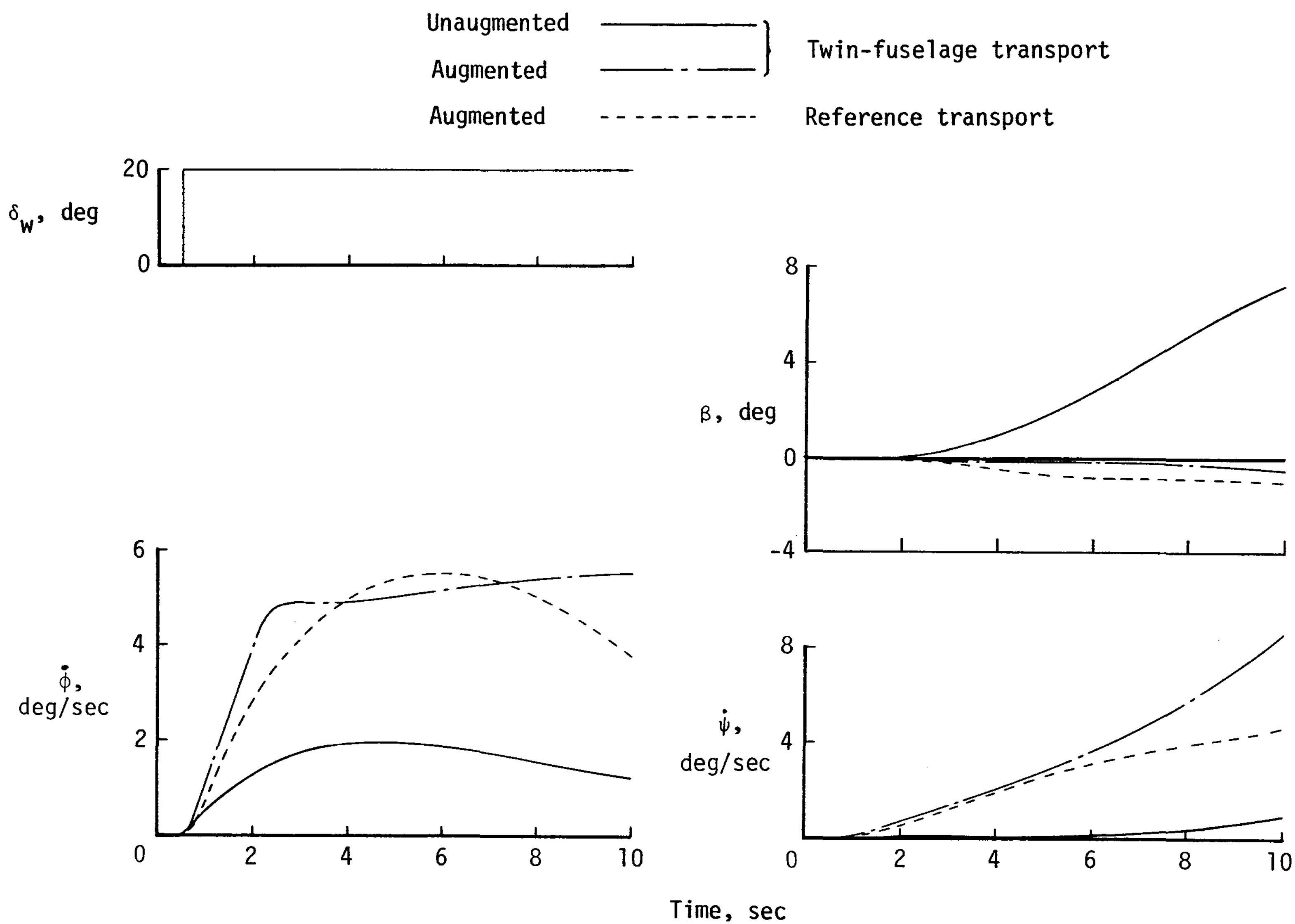
(d) Span-loader transport.

Figure 14. Concluded.



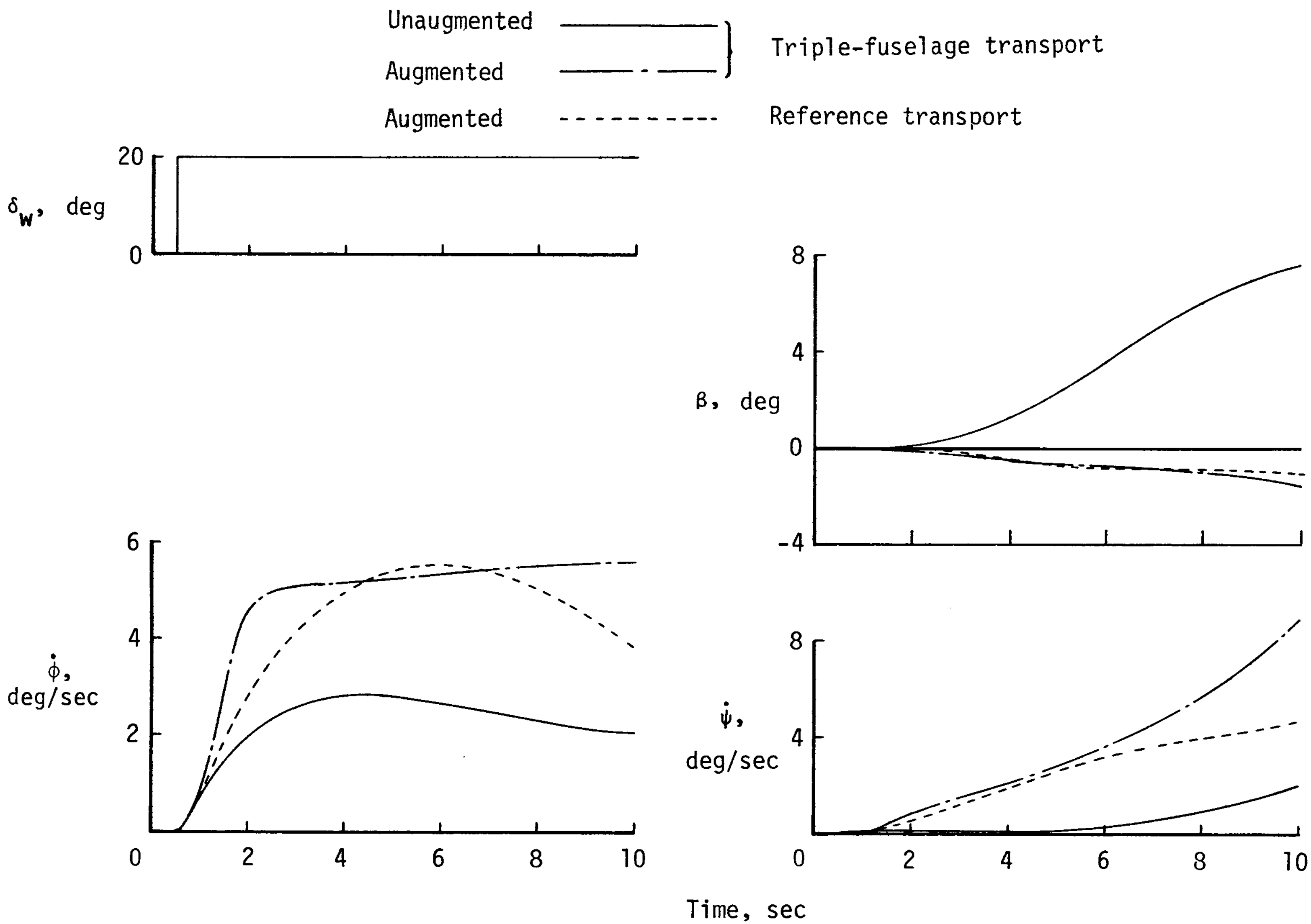
(a) Comparison of unaugmented and augmented very large single-fuselage transport with augmented simulated reference transport.

Figure 15. Lateral-directional response to step wheel input.



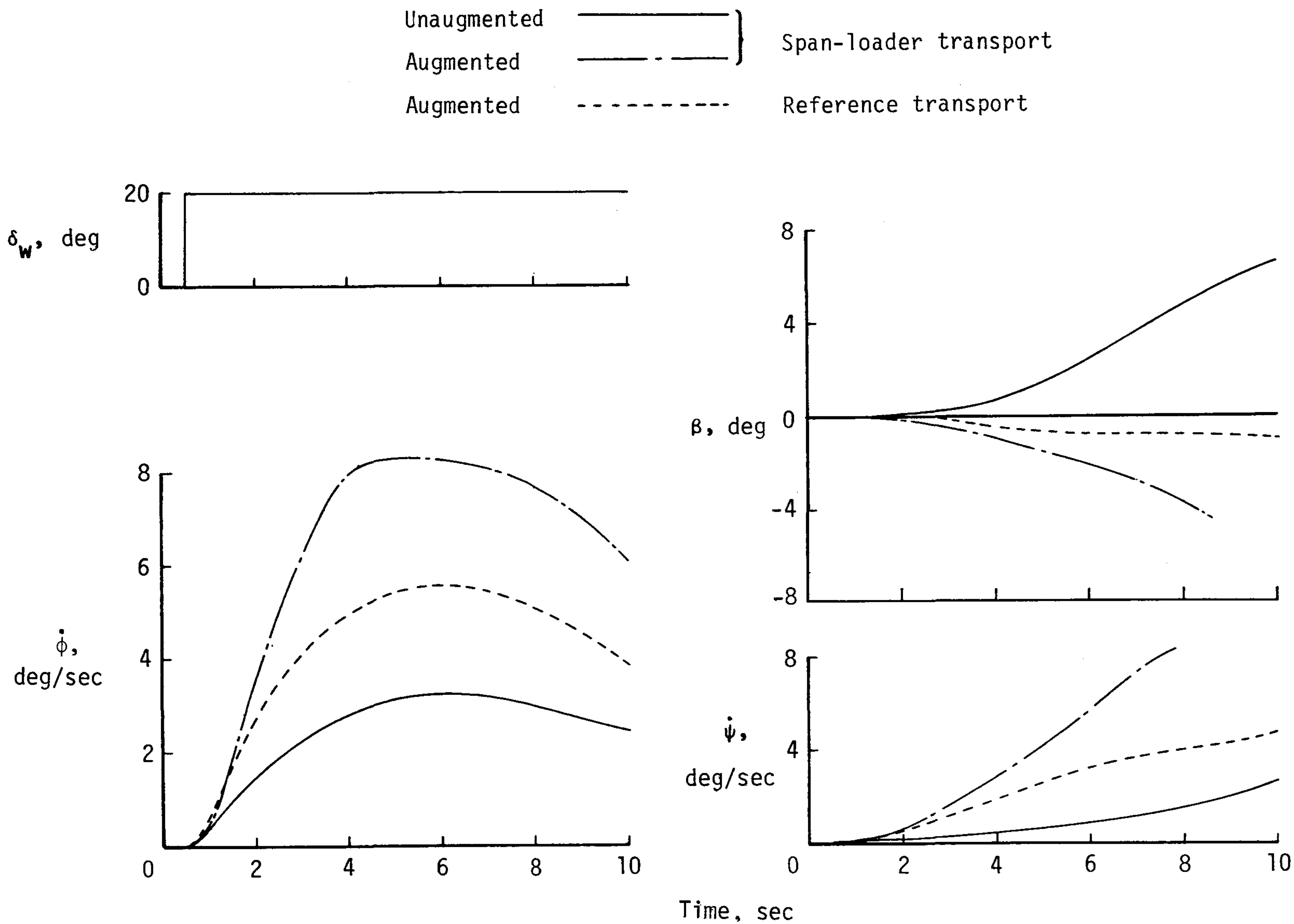
(b) Comparison of unaugmented and augmented twin-fuselage transport with augmented simulated reference transport.

Figure 15. Continued.



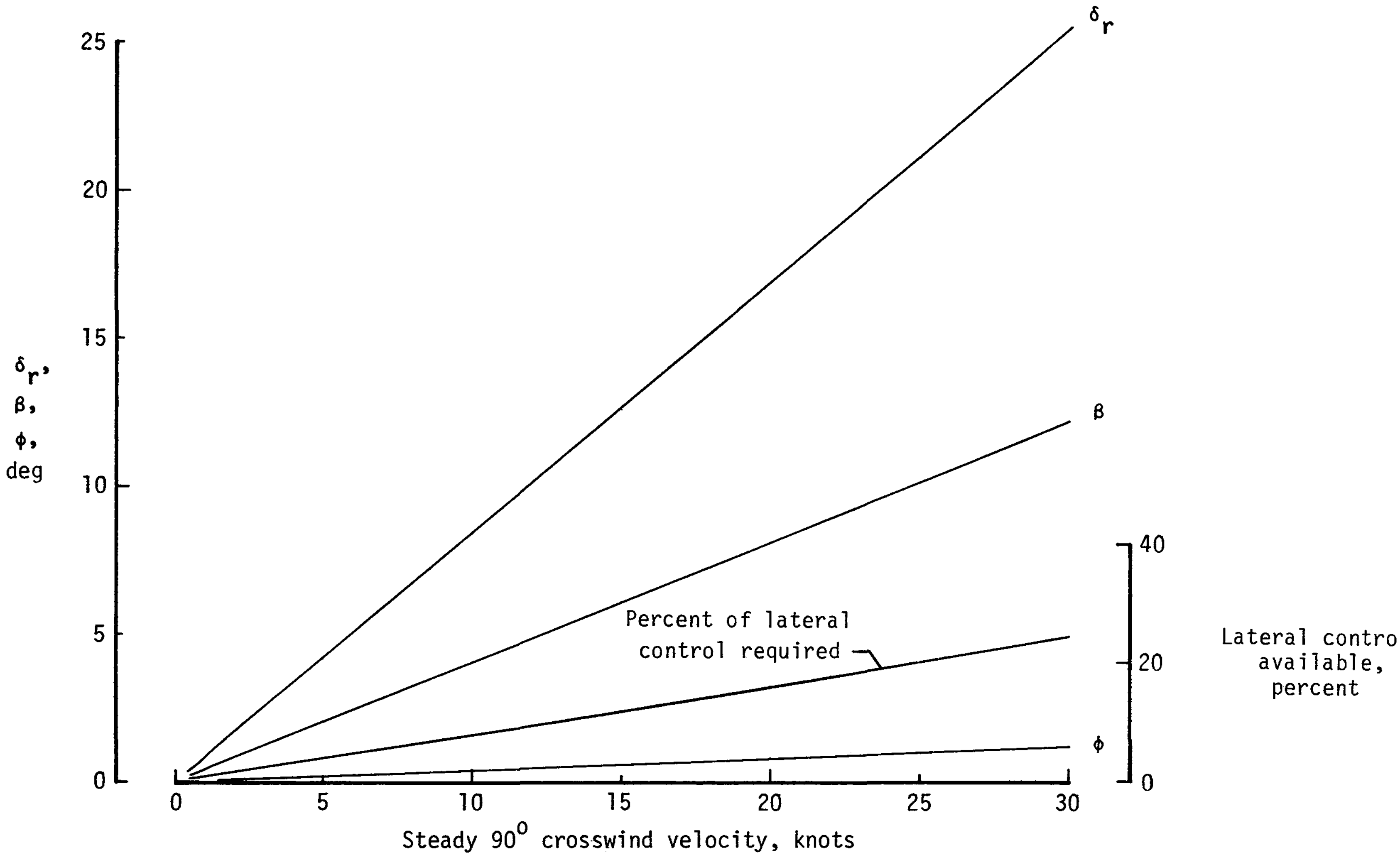
(c) Comparison of unaugmented and augmented triple-fuselage transport with augmented simulated reference transport.

Figure 15. Continued.



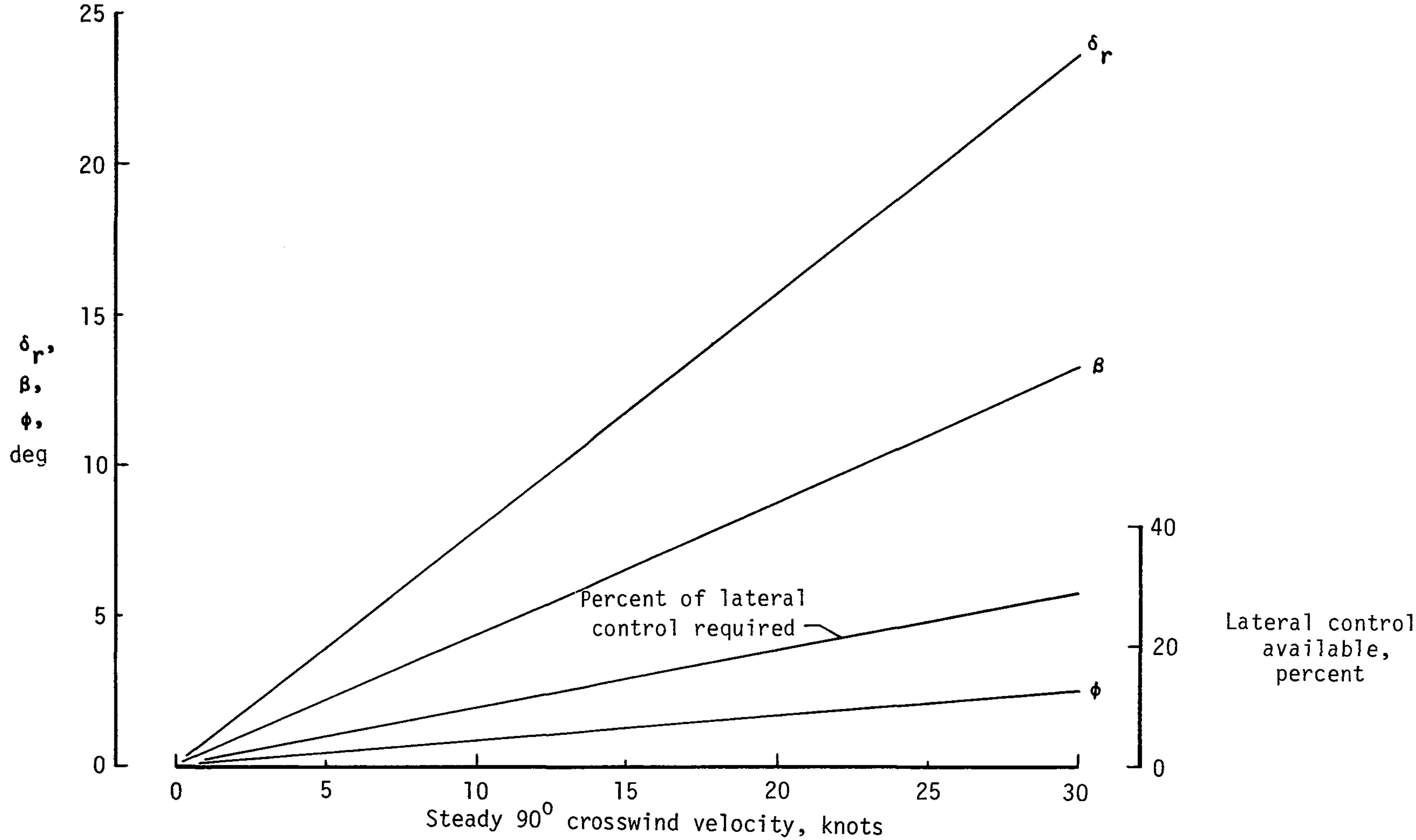
(d) Comparison of unaugmented and augmented span-loader transport with augmented simulated reference transport.

Figure 15. Concluded.



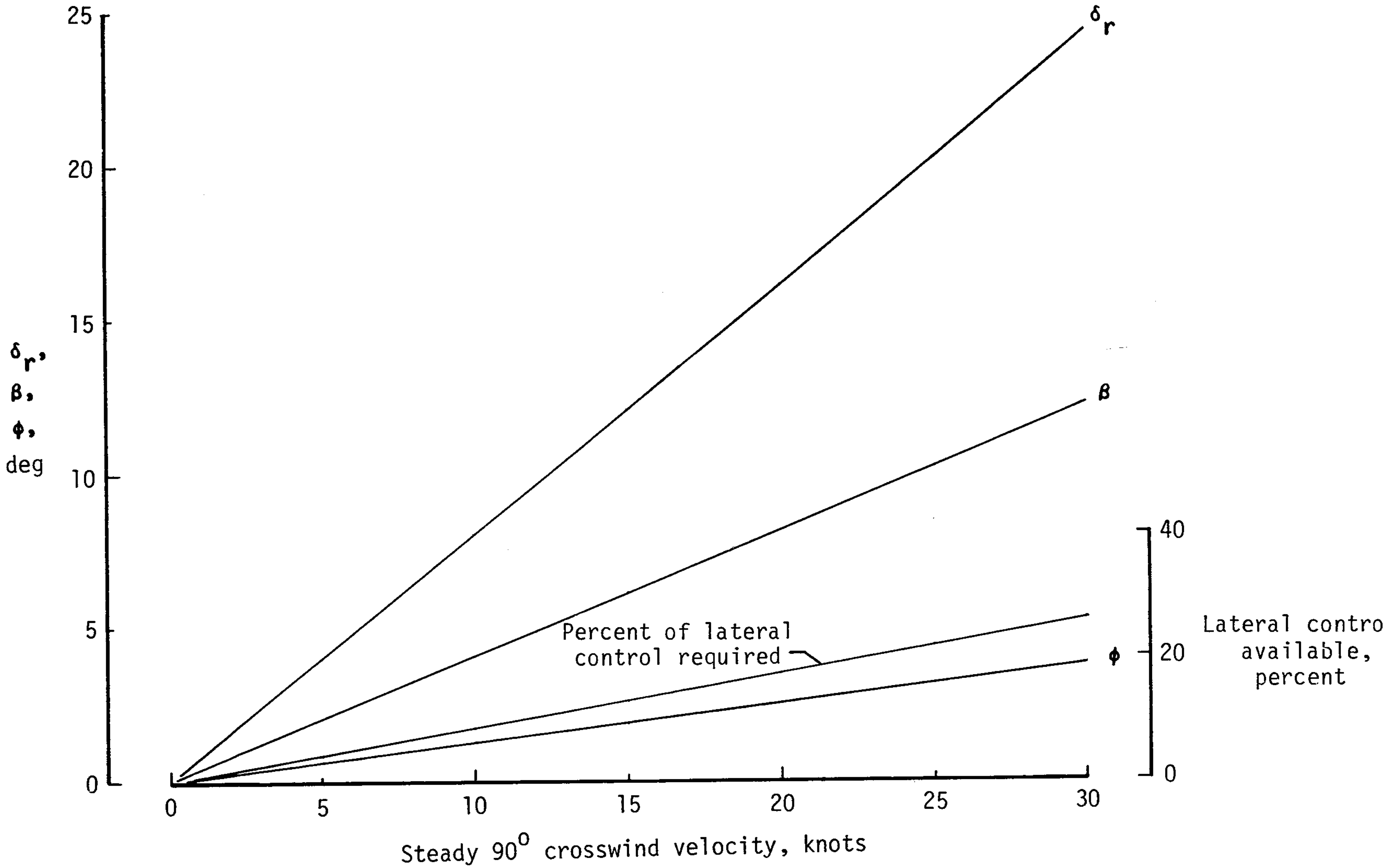
(a) Very large single-fuselage transport.

Figure 16. Indication of crosswind trim capability of simulated airplanes.



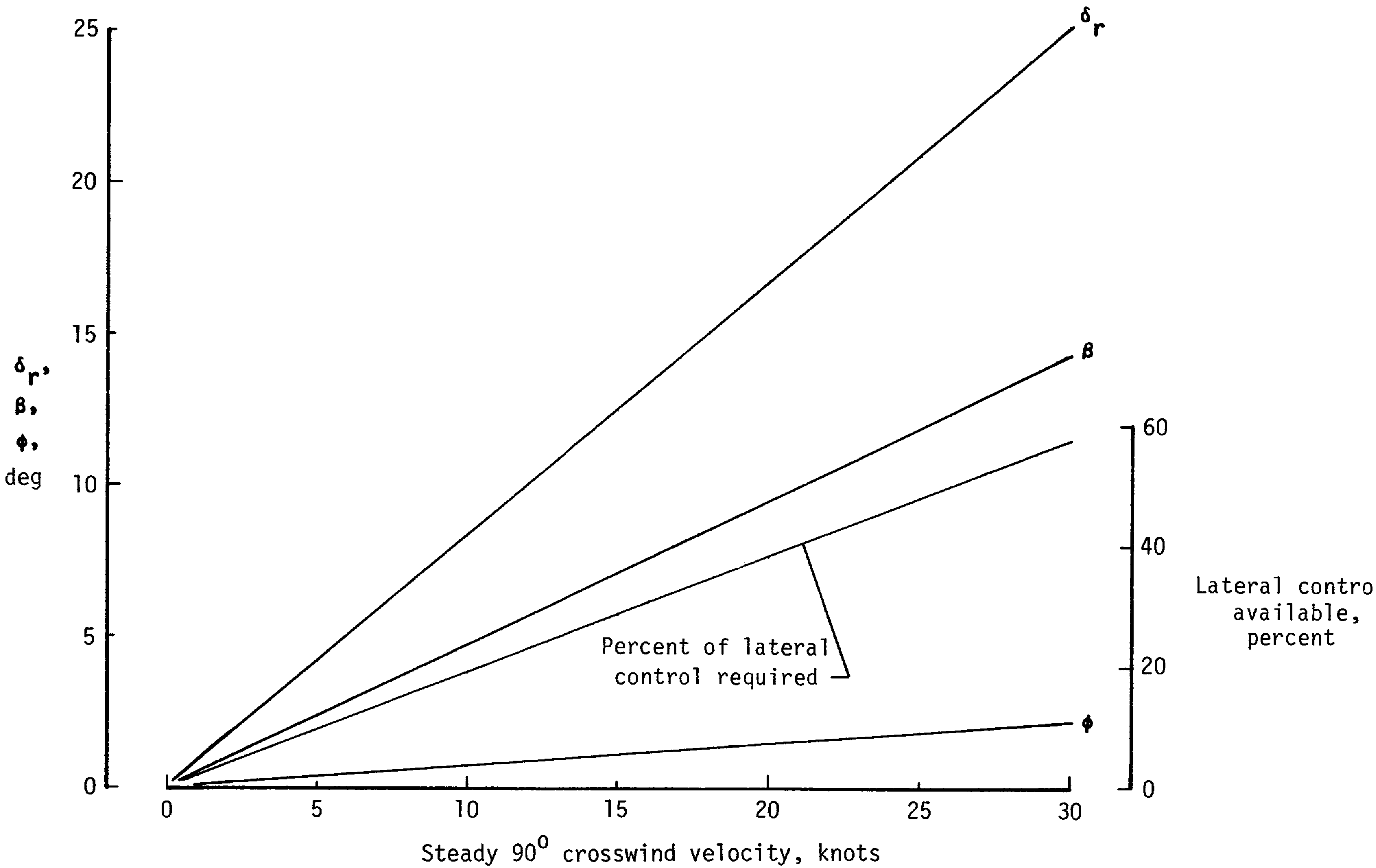
(b) Twin-fuselage transport.

Figure 16. Continued.



(c) Triple-fuselage transport.

Figure 16. Continued.



(d) Span-loader transport.

Figure 16. Concluded.

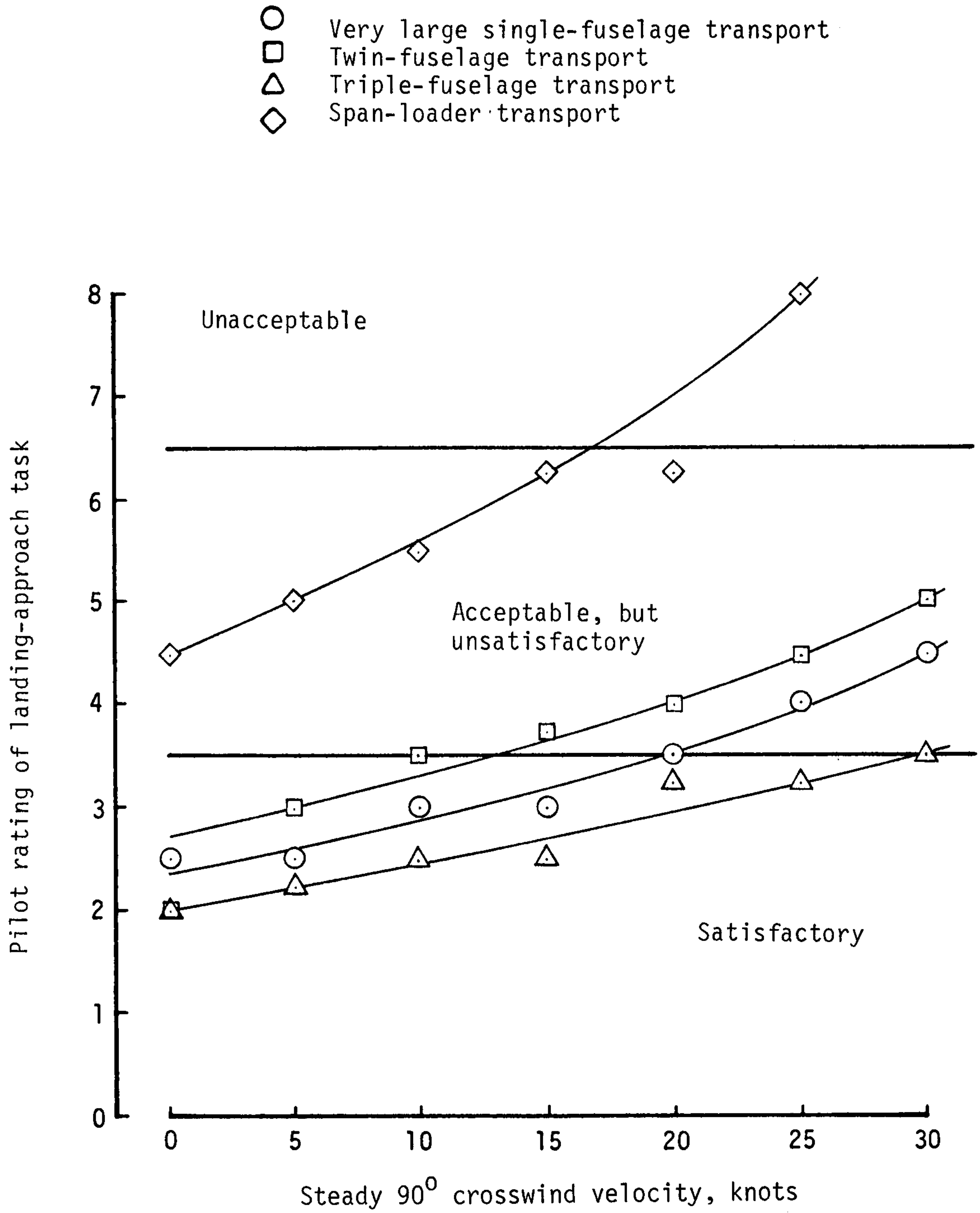


Figure 17. Indication of pilots' ability to land safely in 90° crosswinds.

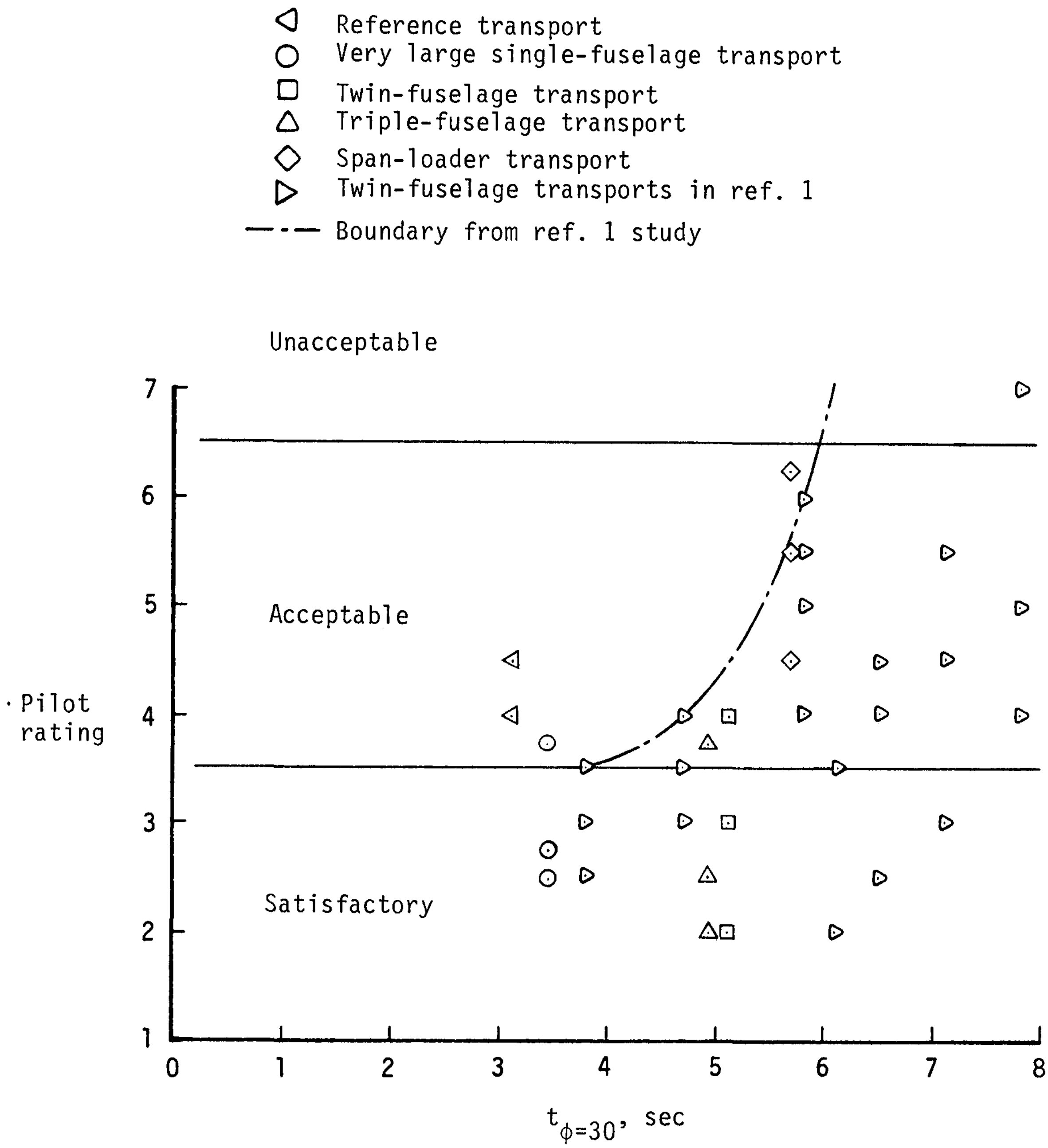


Figure 18. Summary of roll performance from various landing tasks simulated.

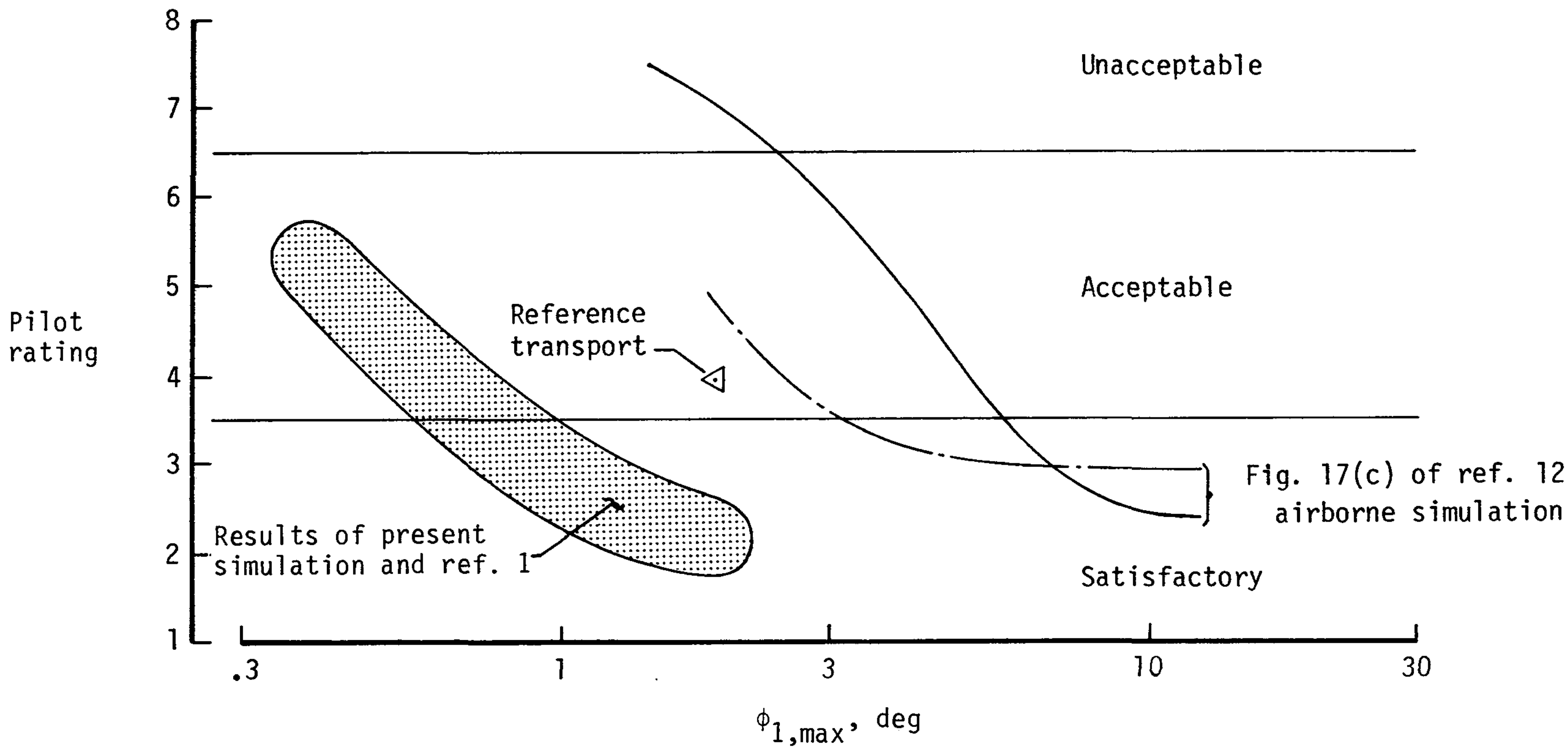


Figure 19. Effect on pilot rating of maximum bank angle attained in 1 sec during landing approach.

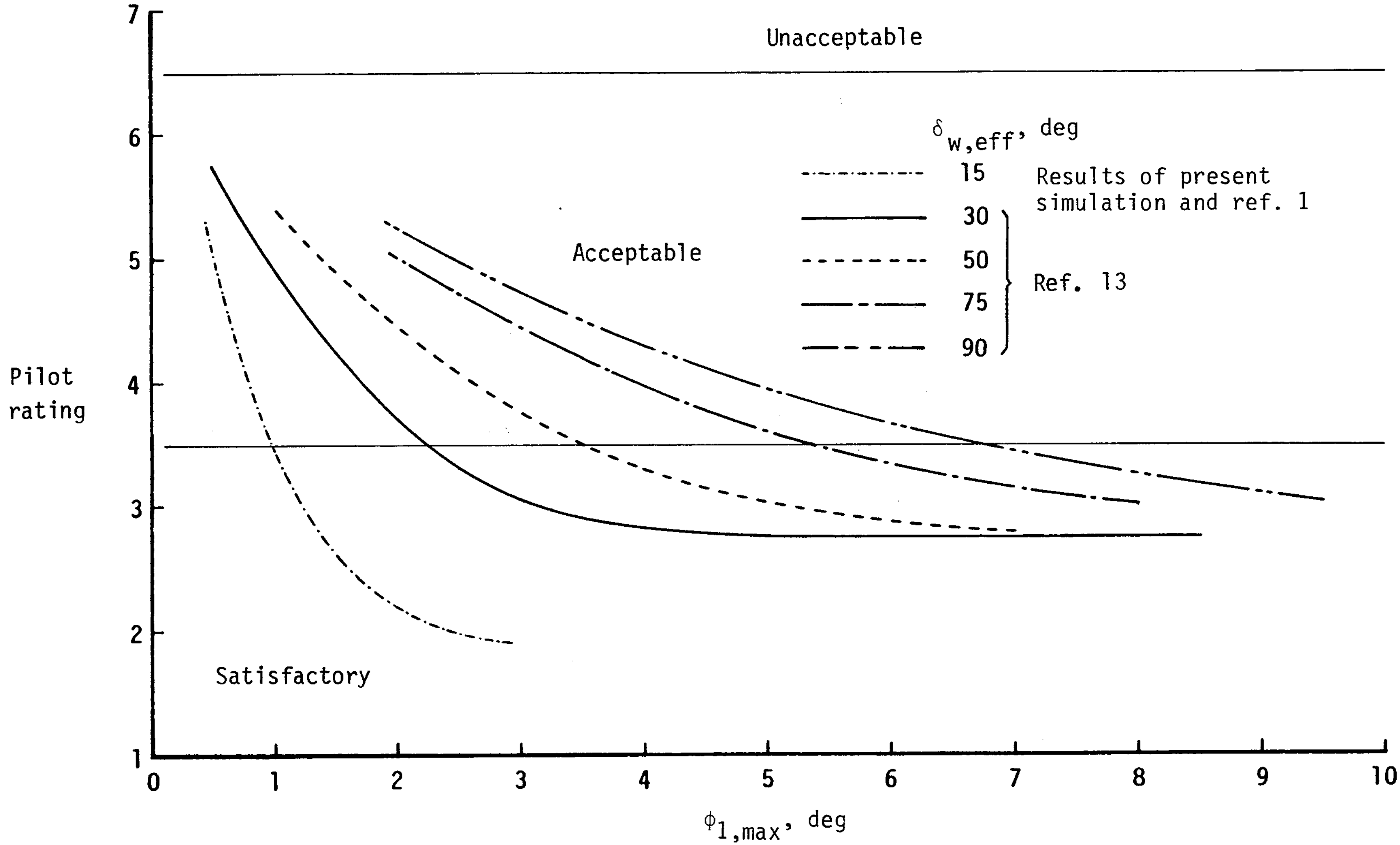


Figure 20. Effect on pilot rating of maximum bank angle attained in 1 sec for various effective lateral wheel angles.

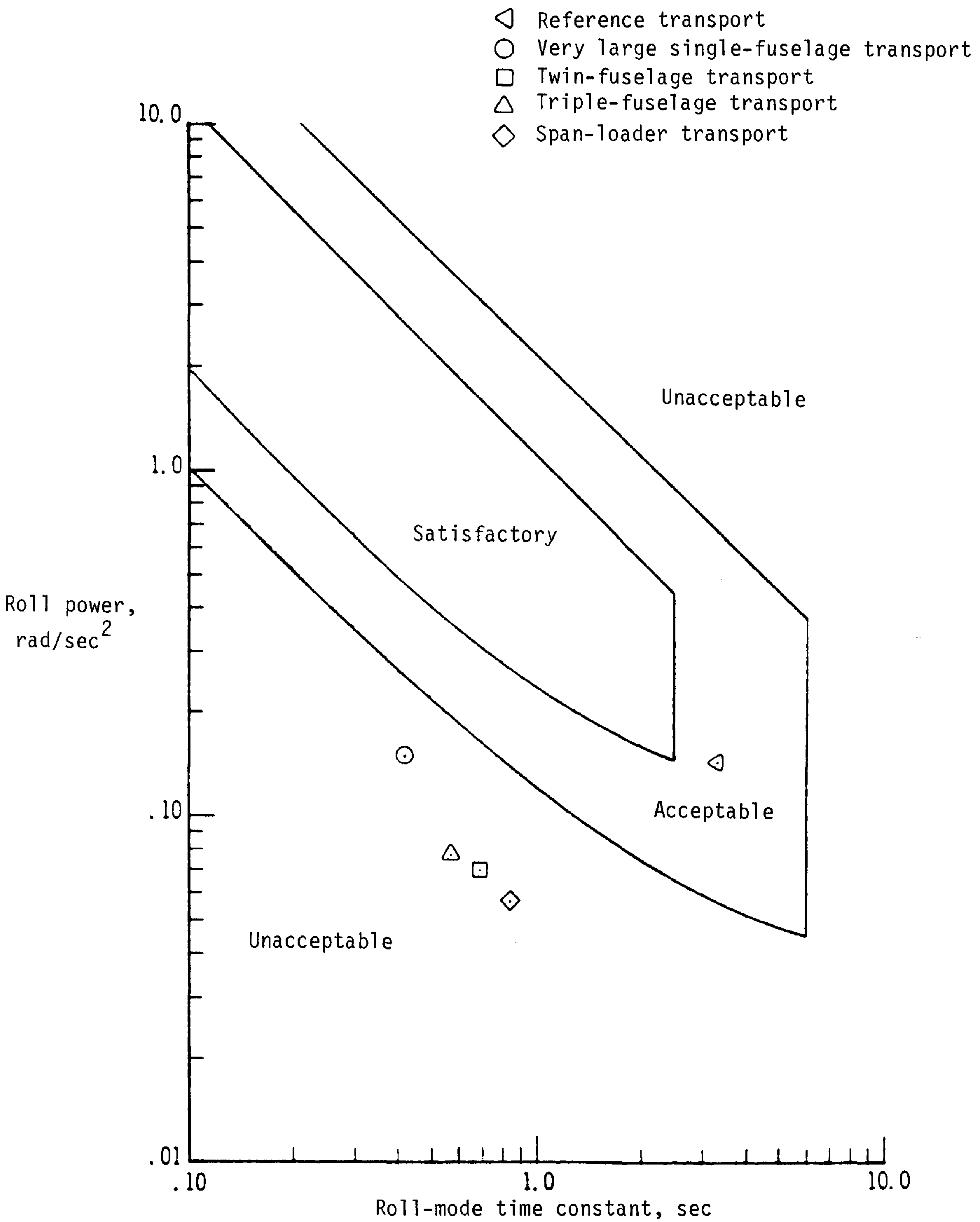


Figure 21. Roll-acceleration response boundaries for large airplanes. Boundaries from reference 14.

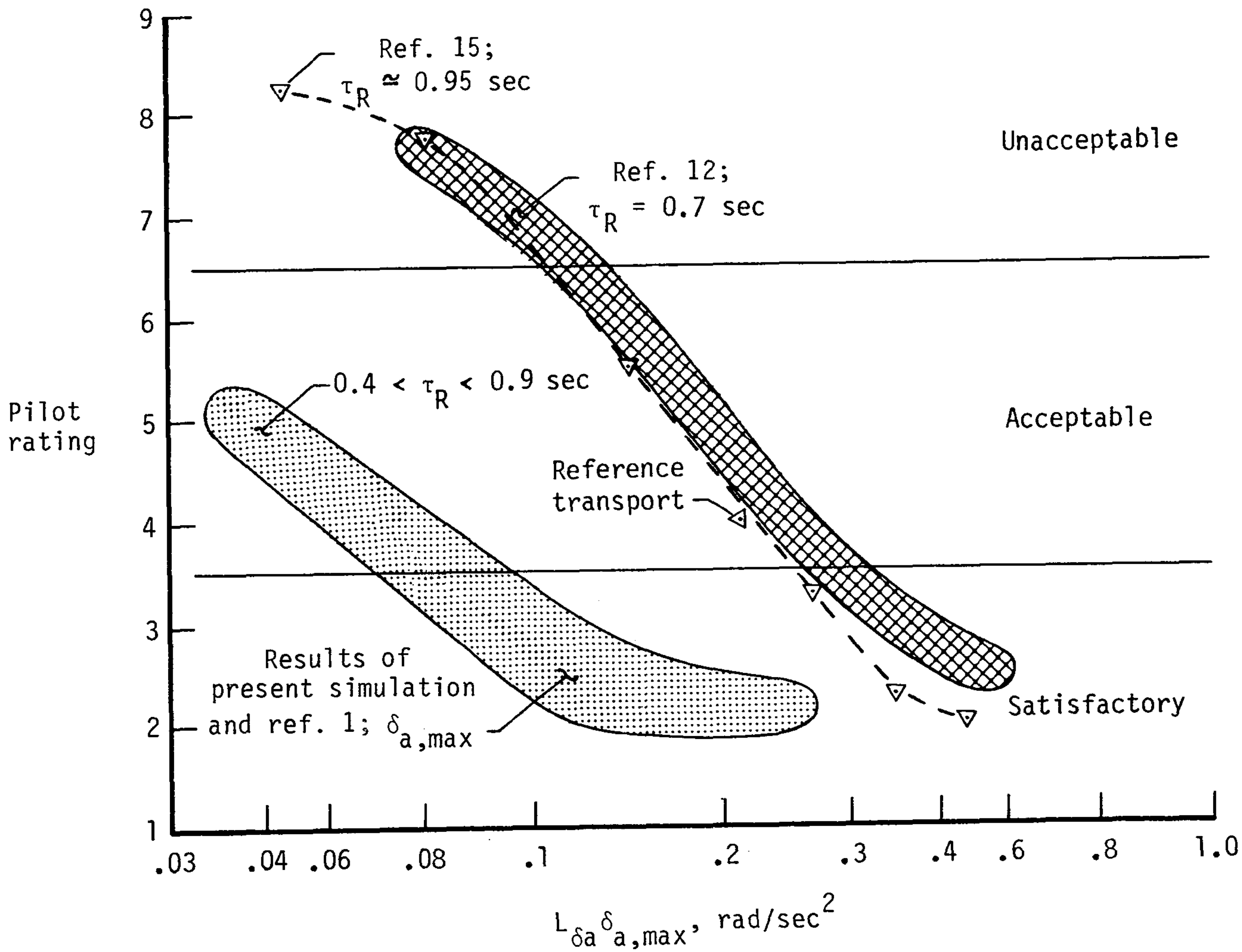


Figure 22. Effect on pilot rating of maximum roll-acceleration capability during landing approach.

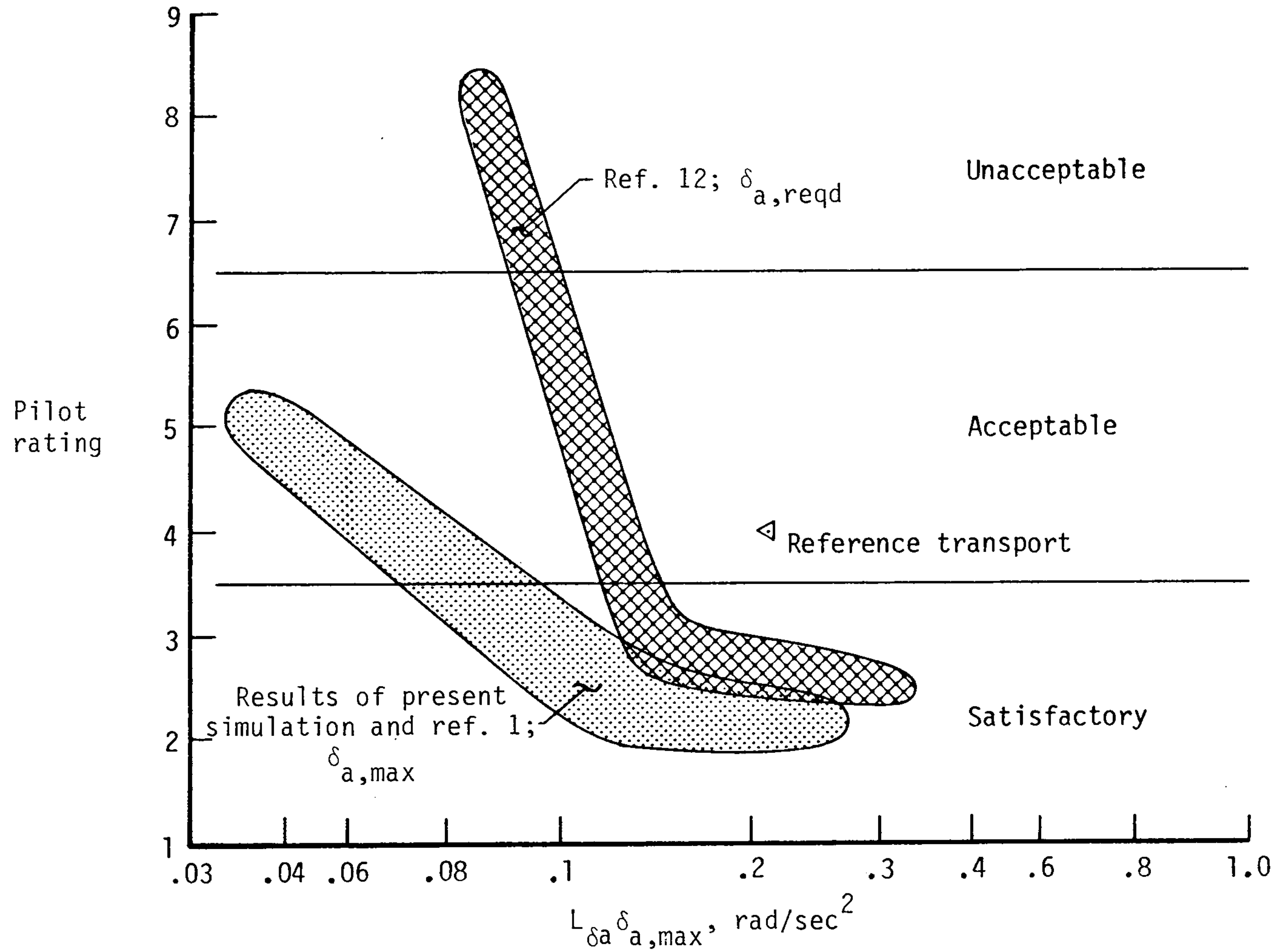


Figure 23. Effect on pilot rating of specified roll-acceleration capability during landing approach.

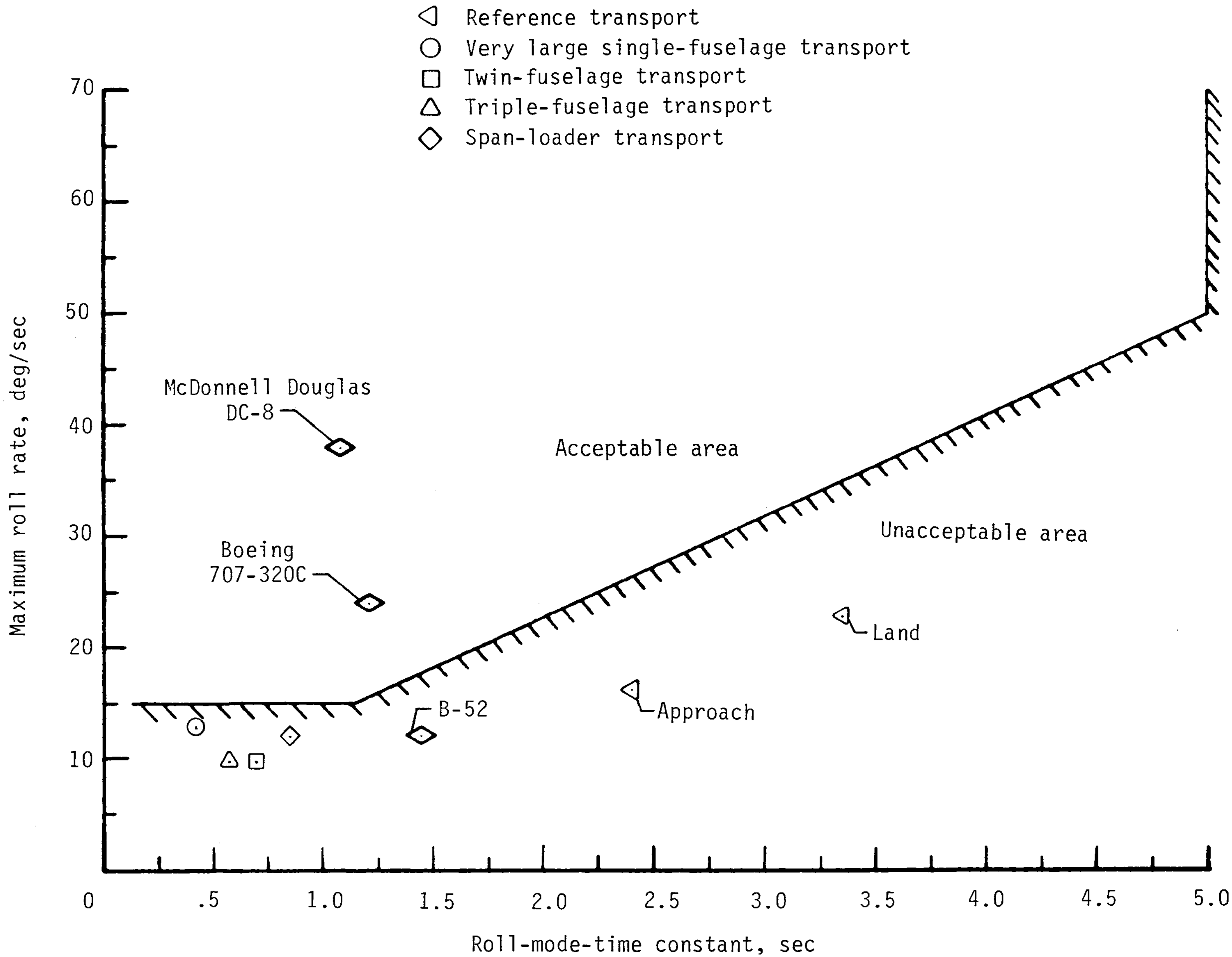
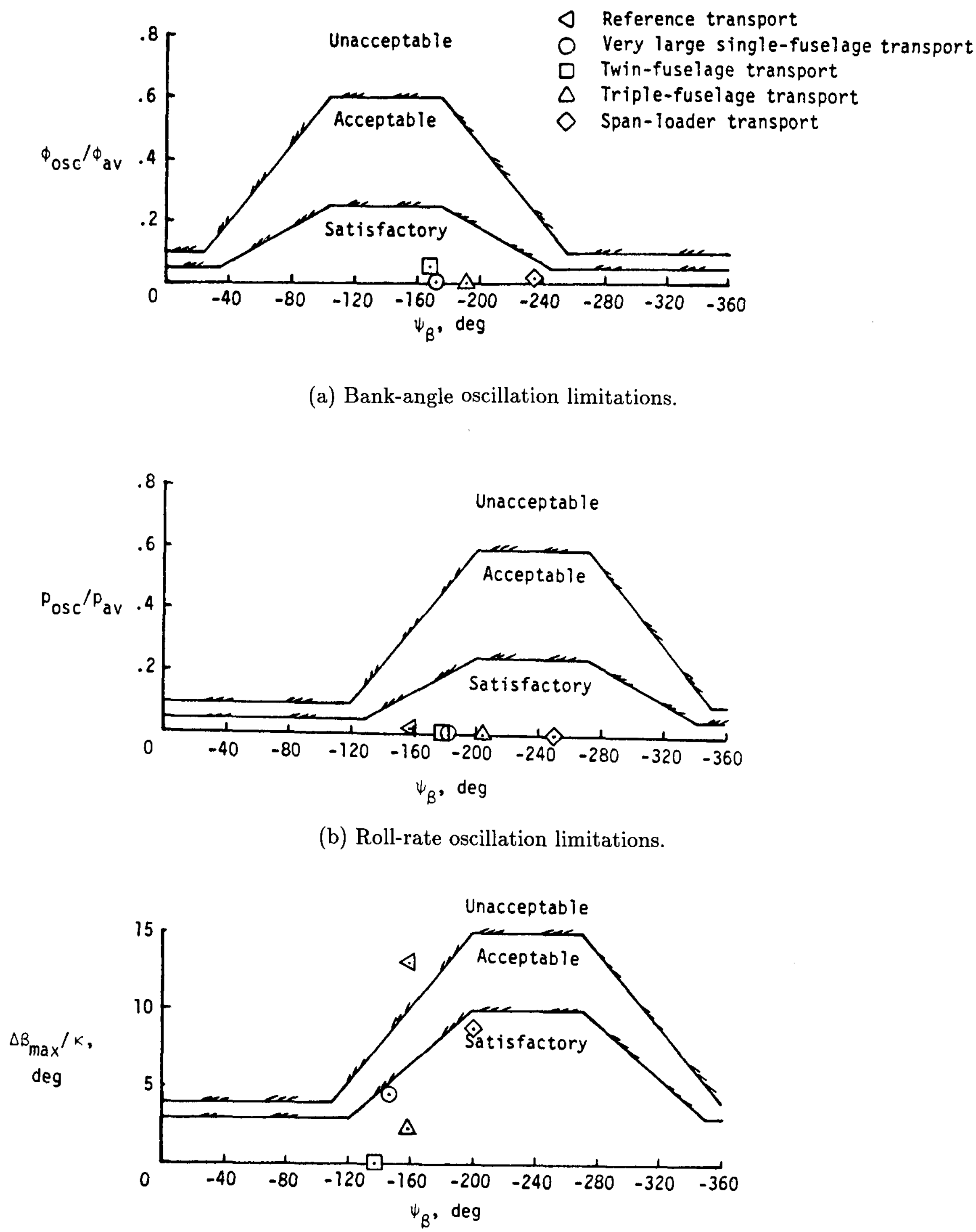


Figure 24. Roll-rate capability criterion for transport airplanes. Boundaries from reference 16.



(a) Bank-angle oscillation limitations.

(b) Roll-rate oscillation limitations.

(c) Sideslip-excursion limitations.

Figure 25. Bank-angle oscillation, roll-rate oscillation, and sideslip-excursion limitations of reference 8. Final approach; SCAS on.

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16. Abstract
In an effort to aid in the future establishment of new stability requirements, a six-degree-of-freedom, ground-based simulator study has been conducted to evaluate the low-speed flight characteristics of four dissimilar cargo transport airplanes, and these characteristics are compared with those of a large, present-day (reference) transport configuration similar to the Lockheed C-5A airplane. The four very large transport concepts evaluated consisted of single-fuselage, twin-fuselage, triple-fuselage, and span-loader configurations. The primary piloting task was the approach and landing operation. The results of this study indicated that all four concepts evaluated had unsatisfactory longitudinal and lateral-directional low-speed flight characteristics and that considerable stability and control augmentation would be required to improve these characteristics (handling qualities) to a satisfactory level. Through the use of rate-command/attitude-hold augmentation in the pitch and roll axes, and the use of several turn-coordination features, the handling qualities of all four large transports simulated were improved appreciably. The ground-based simulation results indicated that a value of $t_{\phi=30}$ (time required to bank 30°) less than 6 sec should result in "acceptable" roll-response characteristics; and when $t_{\phi=30}$ is less than 3.8 sec, "satisfactory" roll response should be attainable on large airplanes such as those evaluated in this study.

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